Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0293

REAPPRAISAL OF THE SEISMOTECTONICS OF SOUTHERN ONTARIO TASK 1: RELOCATION OF EARTHQUAKES AND SEISMICITY PATTERN

by

A.A. Mohajer
Univ. of Toronto and Seismican

A research report prepared for the
Atomic Energy Control Board,
Energy, Mines and Resources
and Ontario Hydro

November 1987

MAGNEC
AMNEC

Multi-Agency Group for Neotectonics in Eastern Canada

L'Association Multipartite pour la Néotectonique dans l'Est Canadien

Contribution 87-01

Canada

Research report

1 EXECUTIVE SUMMARY

A realistic assessment of seismic risk is important in design, construction and operation of critical or strategic facilities. Review of up-to-date information and the application of state-of-the-art techniques can reduce the number of uncertainties in seismic hazard studies. These aspects may serve the interest of the community by minimizing the potential damage as well as preventing over-conservatism which is considered to be another type of economic loss even before the earthquake occurs.

The fundamental objectives of this study were to review and improve the seismological data base as an aid in more realistic evaluation of seismic hazard in southern Ontario. For this purpose, the following procedures have been undertaken:

In the first stage, the types of errors in earthquake location files are identified, sources of uncertainties are discussed and a sensitivity analysis of the errors to different parameters is presented. For this analysis and for calibration of the crustal velocity models, recorded data from the 1982 COCRUST seismic experiment explosions at Marmora, Ontario and Bristol Mines, Quebec, and blasts from the Ogden Point quarry at Lake Ontario have been used. Conclusions reached are that the most prominent sources of errors are: a) systematic biasing to different combinations of seismographic stations which have changed through time, b) quality of the input data and consistency in assigned weighting factors, c) variations in station coverage and therefore detection threshold in southern Ontario, and d) to a lesser extent, the crustal velocity models.

In the second stage, a group location technique, Joint Hypocenter Determination (JHD), has been utilized to improve the locations of a group of 67 well-recorded events, mostly from the more active region near the Ottawa River and in western Quebec. The third stage, to relocate smaller and less reliably detected events in southern Ontario, utilized a new algorithm, "HYPOCENTER", which proved very efficient and flexible in the test runs for handling local explosion and natural events. The results show that the latter technique, if used with reviewed and corrected phase data, can yield solutions with accuracy of better than +/-2km, compared with uncertainties in the order of +/-20km observed for routinely located epicenters in the vicinity of Lake Ontario.

A preliminary interpretation of the seismicity patterns in the study region shows that earthquakes of magnitude 3 and larger tend to align along preferred seismic trends which may, in turn, be controlled by weakness planes in the Earth's crust. These inferred trends coincide with dominant northwesterly and northeasterly striking structural directions. Delineation of the dimensions of such planes of weakness helps in the definition of the properties of real seismic sources and may serve as a basis to constrain future seismic potential, including the upper bound magnitudes (M_{max}) which are important fundamental input parameters for seismic risk analysis. For earthquakes smaller than magnitude 4 prior to 1970 and for microearthquakes (M<3) which occurred near the Lake Ontario shoreline, the detection coverage was not sufficient to conclusively discuss accurate locations and causative mechanisms. Nevertheless, the contribution of triggering mechanisms due to pressure transients resulting from groundwater fluctuations and consequent hydraulic fracturing can not be omitted at this stage.

It is recommended that a site-specific seismic study be carried out for all important facility sites in southern Ontario. These studies should include: 1) re-examination of all available original seismograms for the events within a radius of 300km to permit improvement and for more consistent data reduction to be used in recomputation of the locations, and 2) monitoring of local microearthquakes with a dense array of seismographs as a means of verifying the source properties and to develop appropriate constraints for the generation and recurrence of larger magnitude earthquakes.

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1 RÉSUMÉ

Une évaluation réaliste des risques sismiques est important dans la conception, la construction et l'exploitation d'installations critiques ou stratégiques. La révision de données mises à jour et l'application de techniques de pointe peuvent réduire le nombre d'incertitudes dans les études sur les risques sismiques. Ces aspects peuvent servir à la collectivité en minimisant les dommages possibles tout en évitant un excès de prudence qui est considérée comme un autre type de perte économique avant même que le tremblement de terre se produise.

Les objectifs fondamentaux de la présente étude sont de réviser et d'améliorer la banque de données sismologiques comme outil pour réaliser une évaluation plus réaliste des risques sismiques dans le sud de l'Ontario. On procède donc ainsi :

En premier lieu, on détermine les types d'erreurs dans les dossiers sur l'emplacement des tremblements de terre, on traite des sources d'incertitude et on présente une analyse de sensibilité des erreurs par rapport à différents paramètres. Pour cette analyse et pour l'étalonnage des modèles de vélocité crustale, les données enregistrées lors des explosions sismiques expérimentales COCRUST, en 1982, à Marmora (Ontario) et à Bristol Mines (Québec) ont été utilisées, ainsi que les dynamitages à la carrière Ogden Point, près du lac Ontario. On en a conclu que les plus importantes sources d'erreurs étaient : a) la dérive systématique d'après les combinaisons différentes de stations sismographiques qui ont changé avec le temps; b) la qualité des données intrantes et la cohérence des facteurs de pondération assignés; c) la couverture différente selon les stations et, par conséquent, du seuil de détection dans le sud de l'Ontario, et d) à un degré moindre, les modèles de vélocité crustale.

En deuxième lieu, une technique groupée ("Joint Hypocenter Determination"—JHD) est utilisée pour améliorer la localisation d'un groupe de 67 incidents bien documentés, surtout dans la région plus active située près de la rivière des Outaouais et dans l'ouest du Québec. En troisième lieu, pour relocaliser des incidents moins importants et moins bien décelés dans le sud de l'Ontario, on utilise un nouvel algorithme ("HYPOCENTER") qui s'est avéré très efficace et très flexible lors des essais pour

traiter les explosions locales et les incidents naturels. Les résultats montrent que la dernière technique peut indiquer des emplacements à 2 km près, si elle est utilisée de concert avec des données de phase révisées et corrigées, comparativement aux incertitudes de quelque 20 km que l'on peut observer dans le cas des épicentres localisés normalement dans la région du lac Ontario.

Une interprétation préliminaire de la distribution des séismes dans la région à l'étude montre que les tremblements de terre d'une magnitude de 3 et plus ont tendance à s'aligner sur des schémas sismiques privilégiés qui peuvent, à leur tour, être régis par des plans de défaillance dans la croûte terrestre. Ces tendances observées coïncident avec les orientations structurales dominantes vers le nord-ouest et le nord-est. Le tracé des dimensions de ces plans de défaillance aide à déterminer les propriétés des véritables sources sismiques et pourrait servir de base pour contraindre les futurs incidents sismiques possibles, y compris les magnitudes supérieures (M_{max}) qui représentent des paramètres intrants fondamentaux importants pour les analyses de risque sismique. Dans le cas des tremblements de terre inférieurs à une magnitude de 4 avant 1970 et des micro-tremblements de terre inférieurs à une magnitude de 3 qui se sont produits près des rives du lac Ontario, la couverture de détection n'était pas suffisante pour en arriver à déterminer l'emplacement exact et les causes. Néanmoins. la contribution de mécanismes de déclenchement dus aux transitoires de pression par suite des fluctuations des eaux souterraines et de la fracturation hydraulique subséquente ne peut être ignorée à ce stade.

Le rapport recommande de mener une étude sismique particulière pour chaque site d'installation importante du sud de l'Ontario. Cette étude devrait comprendre : (1) le réexamen de tous les sismogrammes originaux disponibles des incidents dans un rayon de 300 km pour améliorer la situation et rendre la réduction des données plus cohérente au moment de recalculer les emplacements, et (2) le contrôle des microtremblements de terre locaux à l'aide d'un vaste éventail de sismographes pour vérifier les propriétés des sources et pour mettre au point les contraintes appropriées en cas d'occurrences ou de récurrences de tremblements de terre d'une magnitude supérieure.

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1 INTRODUCTION

1.1 Background

Reliable estimates of earthquake hazard in southern Ontario and western Quebec have a direct impact on the assessment of seismic risk and subsequent implications on the design engineering, cost benefit analyses and to mitigation of potential losses to the overall community. This crucial task can only be based on an improved understanding of the mechanisms responsible for moderate to severe ground shaking as a result of neotectonic activity in this intraplate environment.

There have been extensive discussions over several decades concerning the nature of the apparent disperse and sporadic seismic activity in eastern Canada. Some of the early assumptions regarding seismicity distribution and consequently earthquake hazard evaluations in eastern Canada have been modified and improved substantially (Basham et al., 1979). Renewed attention to this problem has resulted in new attempts in correlating dispersed seismicity with the available geological information (e.g. Forsyth 1981; Sanford et al.,1985; Hasagawa 1986). Installation of the Eastern Canada Telemetered Network (ECTN) has enabled better defined seismic source models to be derived (Basham et al., 1985). A number of new focal mechanism solutions (Wahlstrom, 1987) together with compilation of stress distribution data (Adams, 1987) and formation of the Multi-Agency Group for Neotectonics of Eastern Canada (MAGNEC) are among the recent contributing steps to improve and validate the estimates for location, severity, and likelihood of the future ground motions in this region. Nonetheless, there are many problems and uncertainties in the available data base and in the approaches to seismotectonic interpretations which may have direct impact on the quantitative earthquake hazard assessment in eastern Canada in general, southern Ontario and the more active adjacent region, the West Quebec Seismic Zone (Basham et al., 1979; 1985), in particular.

One of the fundamental problems with both the deterministic and probabilistic approaches to hazard evaluation is the accuracy limits with which the location of the past earthquake and subsequently the future risk are determined. A review of the sensitivity of the hypocenters to different input parameters and a discussion of the methods to improve their locations has been the main theme of this study. The present report covers the contracted Task 1 for a complete seismotectonic reappraisal of southern Ontario proposed in December, 1986.

1.2 Objectives

The fundamental goal throughout the course of this study has been an attempt to identify the sources of uncertainty in earthquake locations and to test the latest methods for improving the data base in order to characterize the seismicity patterns and seismotectonic framework of southern Ontario and of western Quebec. The results of such a study may be used to define and characterize seismic sources, and to constrain the maximum potential magnitudes which are among the necessary input parameters for hazard evaluation and risk analysis.

To fulfill the above objectives, the data compilation, data reduction, analysis and presentation of the results have been set out in the following organization:

After a brief introduction and mention of the objectives in section 1, section 2 of this report discusses the types and sources of mislocation error, develops two crustal velocity models across the Ottawa Bonnechere Graben and carries out a sensitivity test and calibration using the experimental explosion data. In section 3, the relocation procedures and results of the JHD and HYPOCENTER recomputations are presented. Prominent trends in the seismicity patterns and preliminary seismotectonic relations are discussed in chapter 4. A brief account of the current state-of-knowledge of the causative mechanism of intraplate seismicity is also given in this section. Conclusions and recommendations for further investigations are presented in section 5.

2 ANALYSIS OF THE MISLOCATION ERRORS

Published seismicity maps of eastern Canada show a dispersed pattern of historical and instrumental earthquake distribution in western Quebec and southern Ontario (e.g. Figure 2.1; Seismological Service of Canada Bulletins, 1970-1983; Basham et al., 1979; Forsyth, D. 1981; Basham et al., 1985). In this section, an examination of the influence of mislocation of events on shaping an image of apparent random seismicity in the study region is given. For this purpose several possible types and sources of errors have been identified, discussed and tested in the following subsections.

2.1 Source of Errors in the Seismic Data

There are three general types of errors which might be present in the published seismicity data:

First, it was conceivable that individual events within a set might be mislocated with respect to each other, due to different network biases being associated with different combinations of stations that recorded the individual events. This type of error was also noticed when locations of the 1982 COCRUST explosion (Mereu et al., 1986) were calculated using different combinations of the recording stations. This source of relative errors may affect location accuracy of the present seismographic network as well as the data files of different periods. For example, the Eastern Canadian Telemetered Network (ECTN) started with three stations (OTT, MNT and MNQ) in 1974, which improved the detection threshold and accuracy of hypocentre determinations considerably. Stations covering parts of southern Ontario are WBO installed in December 1980, CKO in January 1981 and WEO in April 1982 (Shannon et al., 1983). Potential mislocation of events increases backward through time prior to 1978. Another turning point in the history of earthquake detection and accuracy of location determination in eastern Canada is in the mid-fifties when seismographs in Ottawa and Montreal were installed, but the early phase readings remained inconsistent and less accurate when compared with data files after 1964 and particularly after 1978 (Wetmiller, personal communication). For the data file prior to 1954, instrumental time marks are not as reliable as the recent ones and therefore this inherent inaccuracy may not be rectified by re-examining the original records (Halliday, personal

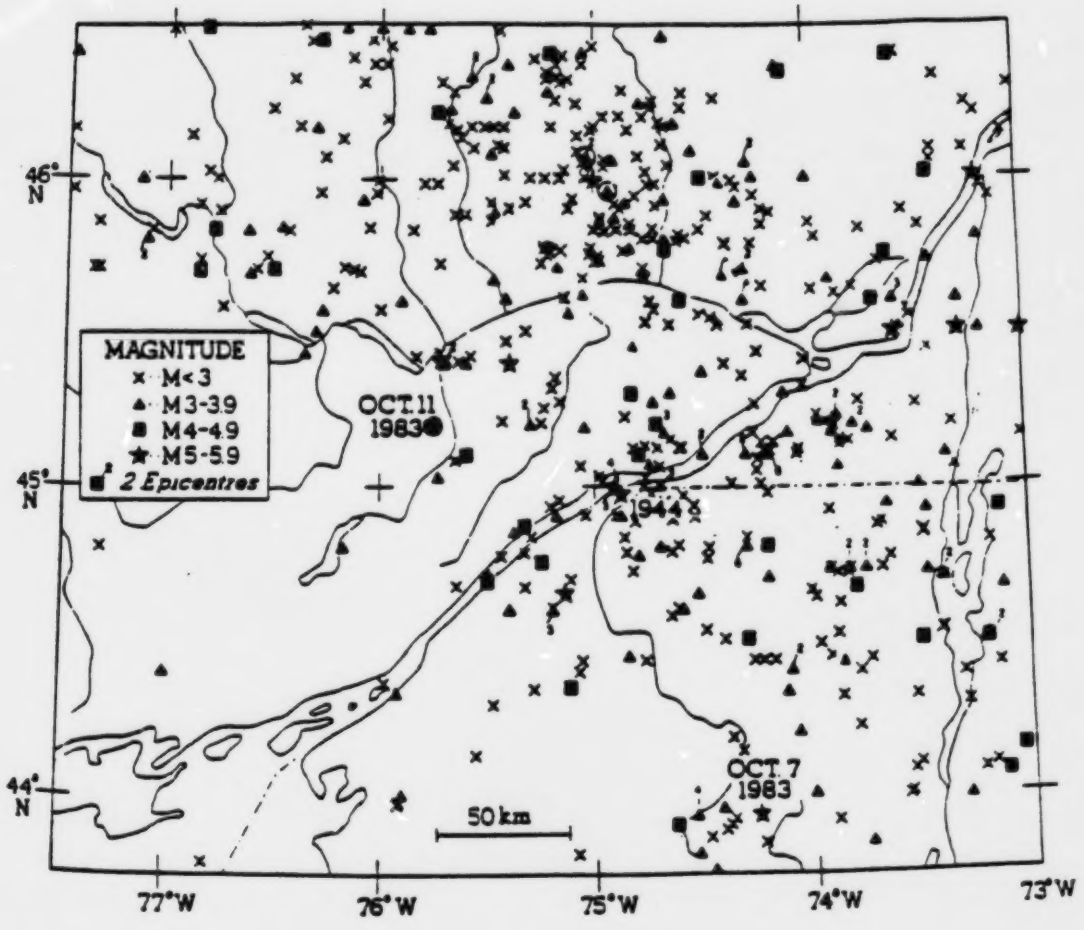


FIGURE 2.1: Background seismicity ; all known events based on Smith (1962, 1966) and bulletins from the GD previously the EPB. Large earthquakes in 1944 and 1983 (7 October) are identified, so is the calibration event of the present study on 11 October 1983. (after Wahlstrom 1987).

communication). The data base is therefore inhomogeneous in time and should be partitioned into at least four subsets according to the seismographic stations covering southern Ontario available at a given time: a) events prior to 1954, b) events between 1954 and 1974, c) events between 1974 to 1982, and d) events after 1982.

A second type of error is due to systematic mislocations associated with the regional variation of station distributions or azimuthal coverage of the events. Comparison between the actual and computed locations for explosions of 1982 seismic experiments near Bristol Mine, Quebec and Marmora, Ontario (Mereu et al., 1986) and for that of the Ogden Point quarry blasts near the Lake Ontario shore show that the mislocations are larger toward the south (Table 2.1). Observed maximum mislocation of the explosions, near Ottawa has been in the order of 15km whereas, mislocation of about 25km and 30km has been observed for the Ogden Point quarry blasts and for an Ontario Hydro construction explosion at Wesleyville on the shore line of Lake Ontario respectively (Table 2.1; Figures 2.2, 2.3). The increased mislocation errors toward the south are mainly because of marginal coverage "for small magnitude events". by existing seismographic stations.

A third type of error is classified as undetected errors in the arrival-time data. Phase identification is sometimes uncertain due to the manmade and/or natural noise sources which are found nearby to some of the stations. Record analysts usually designate a quality code for each phase reading, which should be incorporated with varying weights in computations. Possible misinterpretation by different record analysts, mistyping, or time base corrections may also be sources of mislocation which may be difficult to avoid in routine processing of a large volume of daily data produced by the permanent network. However, for special projects and site specific studies a systematic review by one expert of the original recorded phases for selected events is advisable and may improve the earthquake locations significantly. A test of the sensitivity of the mislocated explosions to the improved input data is presented in Table 2.1 and Figures 2.4 and 2.5. It is shown that by discarding or assigning lower weights to the poor phase readings (normally quality C +/-4 sec) or the ones with high residuals in the first run, generally better locations, with about 2 times improvement in accuracy, may be obtained. Such improvement is only possible where a sufficient number of stations remains to give a stable solution for recomputation. Examples given are reduced mislocations of the explosions of the 1982 seismic experiment after the first step attempt to improve the data quality by deletion of uncertain phases (Table 2.1).

Table 2.1.Sensitivity Test Of the Recomputed Locations for the Explosions of 1982 COCRUST Seismic Experiment and Quarry Blasts

Shot Location		Date and Time					Mislocations(Km)				
coordinates		Mo	Dy	H	Min	Sec	GSC	DQ	VL-D	VSO	VWQ
Marmora	(1)	8	5	10	25	.210	9.5	7	5	1.5	6
44.478 -77.658	(2)	8	7	10	25	.210	2.5	3.5	4.5	2	3.5
1982	(3)	8	11	10	25	.210	16.5	11	6.5	7	9.5
Bristol	(1)	8	5	11	35	.210	9.5	9.5	8	8	9
45.503 -76.339 1982	(2)	8	7	10	15	.210	10.5	3	2	3	2.5
Ogden Point											
43.983 -77.883	(1)	4	22	18	49		15.5	!	14.5	13.5	-
	(2)	6	24	15	39		17.5	!	17.5	16.5	-
1983	(3)	5	31	17	35		20.0	!	20.0	20.5	-

GSC: Locations given by the Geophysics Divisions,(GD) Geological Survey of Canada (GSC), Ottawa, Appendix A.

DQ: Data quality of the reported phase arrivals were considered, stations with high residuals discarded, and "Standard" velocity model of the GD/GSC (Wetmiller et al., 1983) was used in recomputed locations.

VL-D: Velocity model currently used by the Lamont-Doherty Geological Observatory (Table 2.2).

VSO: Velocity model developed for Southern Ontario (Table 2.2).

VWQ: Velocity model developed for Western Quebec (Table 2.2).

!: Not sufficient station and phase arrivals to improve the input data quality. Similar results were obtained for quarry blasts at Milton, Nephton, and Wesleyville.

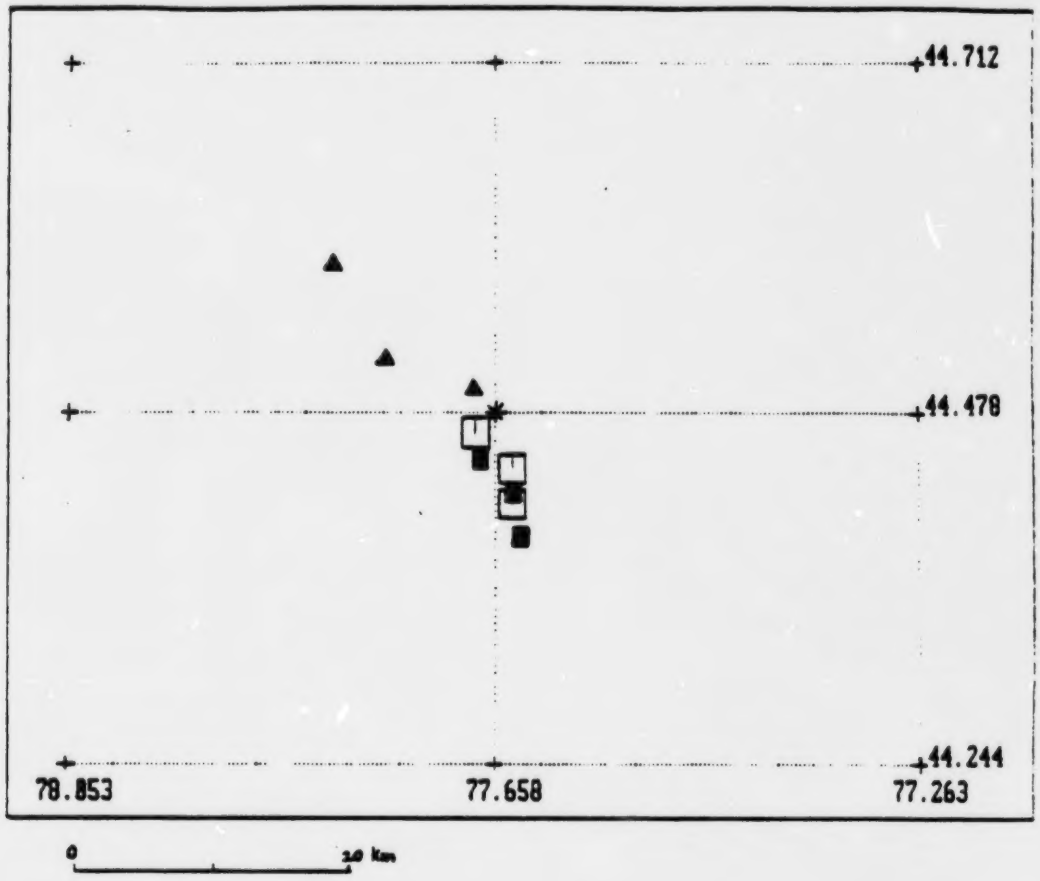


Figure 2.2: Sensitivity of the computed locations of the 1982, COCRUST explosions (Marmora site *) to the input data quality and velocity models.

▲ Locations given by the GD/GSC

□ Recomputed locations using improved input data

■ Recomputed locations using improved input data and VWQ velocity model for western Quebec

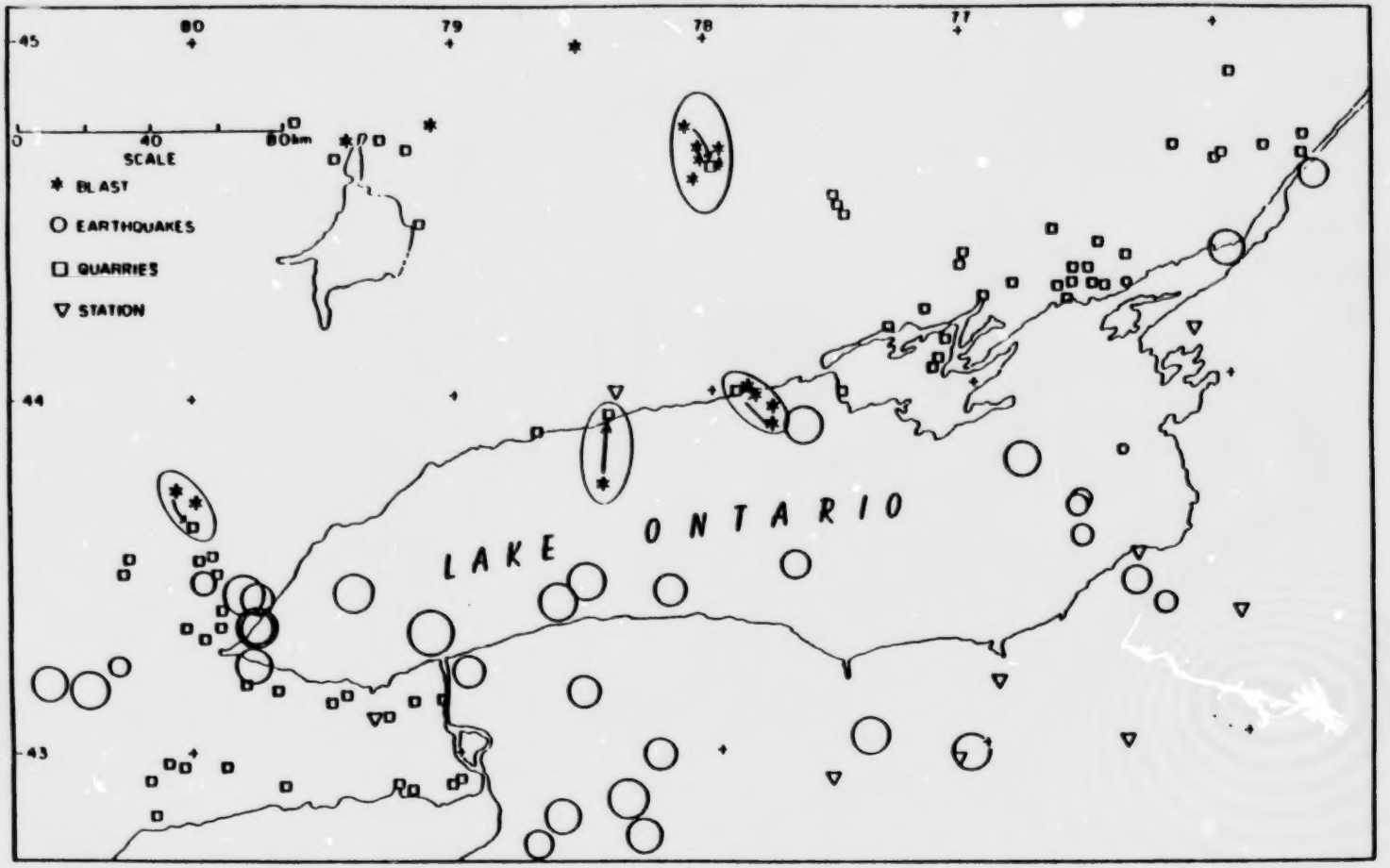


Figure 2.3: Seismicity of southern Ontario (1970 - 1987) and examples of the quarry blasts mis-locations.

2.2 Sensitivity to the Crustal Velocity Models

Variation of the crustal velocities with depth and also laterally has been demonstrated by numerous seismic experiments and is considered to be another source of error in hypocentre determinations. A single-layer "standard" velocity model is currently used by the Geophysics Division of Geological Survey of Canada (GD/GSC) for routine location of earthquakes in eastern Canada (Table 2.2). There have been some remarks on possible small revisions to this model by Horner et al., (1978). The use of slightly higher Lg wave velocity has been proposed by Wetmiller and Cajka (in press) on the basis of 1984 explosion travel-times of the Kapuskasing uplift seismic experiment recorded on a local network in northern Ontario. In the above report, Wetmiller and Cajka indicate that such variations in crustal structure for different regions will lead to mislocation of earthquakes up to 20km or more. A similar conclusion was reached by Forsyth et al. (1983) that the epicentral uncertainties for the earthquakes in the Timiskaming-Kapuskasing region are about 20km.

In order to test the sensitivity of the location errors against various crustal velocity models in southern Ontario, the explosion data of the 1982 COCRUST seismic experiment (Mereu et al., 1986) have been used (Figure 2.6). Additional data from recorded quarry blasts near the Lake Ontario coastal plane were utilized for this investigation. As discussed earlier, a trimmed and improved set of phase data entries has helped reduce the mislocation error to about 50%. The explosion onset times were used as input data for recomputation of their respective locations in a way that earthquakes are located by the "HYPOCENTER" program of Linert et al., (1986). The same data file was run with different crustal velocity models in order to compare the value of mislocation errors.

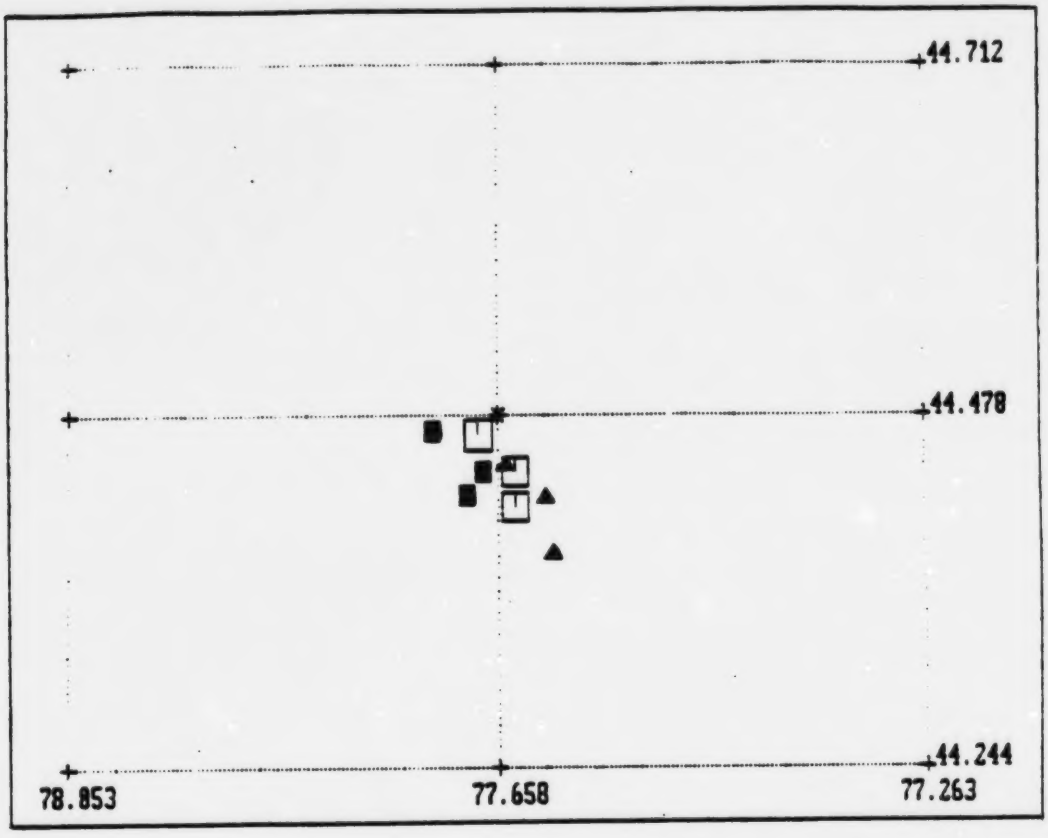


Figure 2.4: Mislocation errors of the 1982 COCRUST explosions (Marmora site *) computed with different velocity models and improved database.

▲ GD/GSC Standard model

■ VL-D Lamont-Doherty Geological Observatory model

⊡ VSO Model suggested for southern Ontario in this study

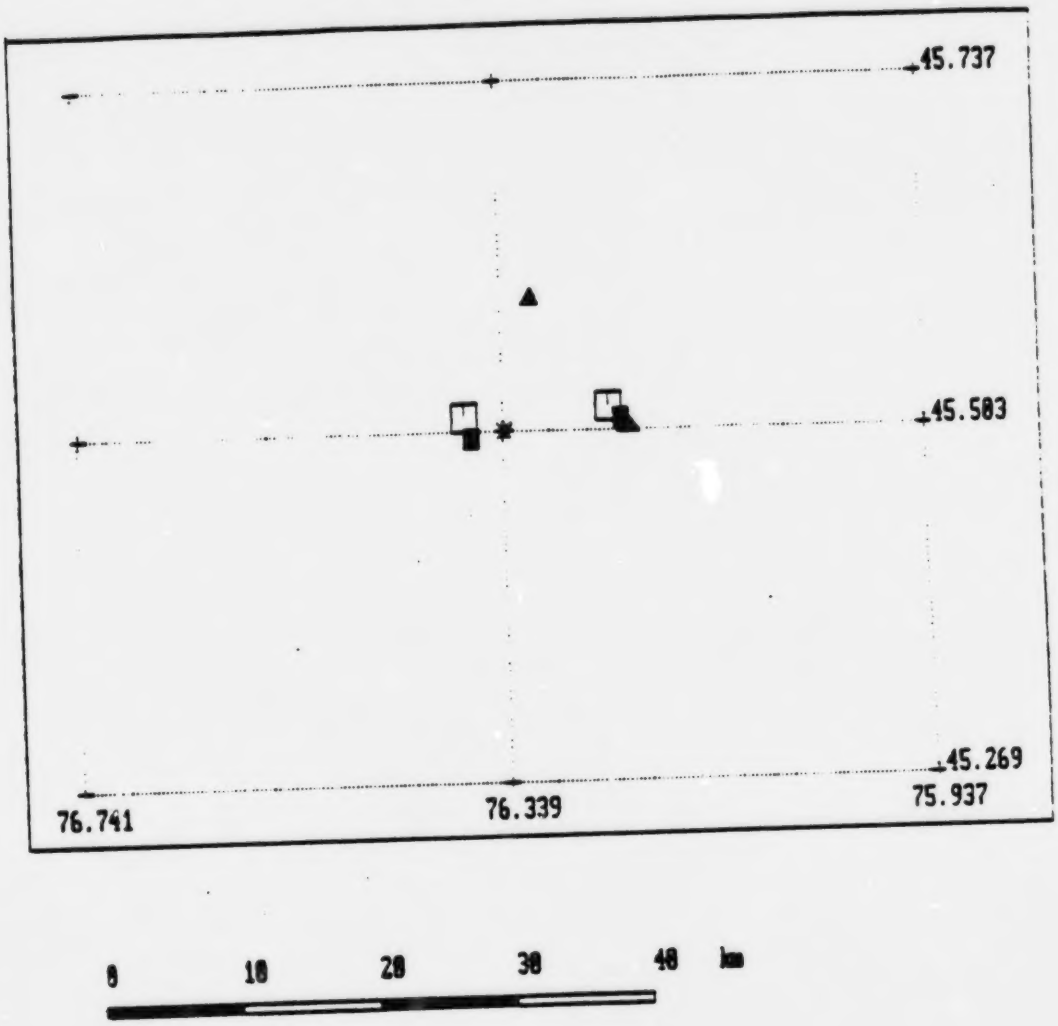


Figure 2.5. Sensitivity of the computed locations of the 1982, COCRUST explosions (Bristol site *) to the input data quality and velocity model.

▲ Locations given by the GD/GSC

⊡ Recomputed locations using improved input data

■ Recomputed locations using improved input data and the velocity model for western Quebec (VWQ)

Table 2.2. Crustal Velocity Models Compared in this Study

	P-Wave Vel. ($km\ sec^{-1}$)	Depth (km)	Thickness (km)
"Standard" Single-Layer Model Geophysics Division, GSC, Ottawa (Wetmiller et al.,1983).	6.2 8.2	00.0 36.0	36.0 1000.0
L-DGO Model: Currently Used by the Lamont - Doherty Geological Observatory, Columbia University, N.Y. (Seeber et al., 1980).	6.10 6.50 8.10	00.0 04.0 35.0	04.0 31.0 1000.0
VSO: Velocity Model Developed for Southern Ontario Using the Results of 1982 COCRUST Seismic Experiment (Mereu et al., 1986), and a Trial and Error Procedure for Further Refinements.	6.1 6.4 6.6 6.8 7.0 8.0 8.2	00.0 01.0 16.5 26.0 32.0 38.0 46.0	01.0 15.5 09.5 06.0 06.0 08.0 1000.0
VWQ: Velocity Model for Western Quebec Developed on the Basis of 1982 COCRUST Seismic Experiment (Mereu et al., 1986) and a Trial and Error Procedure for Further Refinements.	6.1 6.3 6.5 6.7 7.0 8.0 8.2	00.0 04.0 08.5 24.0 30.0 38.0 46.0	04.0 04.5 15.5 06.0 08.0 08.0 1000.0

The crustal velocity models used for this investigation, which are summarized in Table 2.2, include: The "standard" single-layer crust currently used by the GD/GSC for preparation of routine bulletins reporting earthquakes in eastern Canada (Wetmiller et al. 1983); a two-layer crust, currently used by the Lamont-Doherty Geological Observatory of Columbia University, N.Y. for preparation of routine earthquake bulletins reporting events in New York, New Jersey and the eastern side of southern Ontario (Seeber et al., 1980); and two new models developed and discussed in the following paragraphs.

The 1982 seismic refraction profiles across the Ottawa-Bonnechere Graben and the Grenville Front (Mereu et.al., 1987) show lateral variations of the P-Wave velocities as well as significant layering at depths which are reproduced in Figures 2.7-2.8.
A major displacement of the Moho discontinuity is observed at depth, the surface projection of which coincides with the fault zone of the Ottawa-Bonnechere Graben (Figure 2.9). This newly available information served as a basis to develop, test and refine two crustal models for southern Ontario and western Quebec through a trial and error procedure. Examples of the test runs are given in Appendix B and the final results are presented in Table 2.2. The resultant mislocation errors for various crustal models used are given in Table 2.1.

An accuracy of about +/-2 kilometers has been achieved when the well-recorded explosions were relocated using the southern Ontario velocity model (VSO). When the quality of the phase reading has been relatively poor, adoption of a different velocity model was not significantly effective. Nonetheless, corrections of the input data and revision of the weight factors in recomputation improve the mislocation values from 16.5km to 8km. Then further refinements of the accuracy to about +/-2 km may be achieved in some cases with good station coverage.

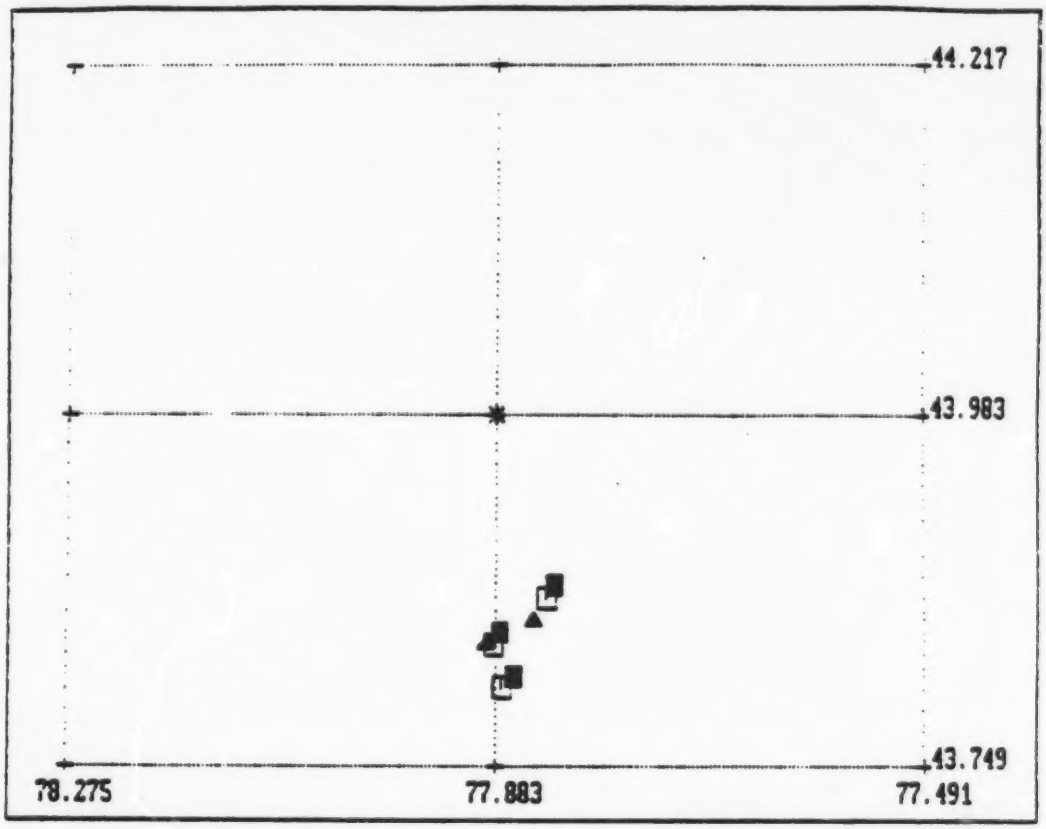


Figure 2.6. Sensitivity of the computed locations of the Ogden Point quarry (*) blast to different crustal velocity models. The original published data prior to corrections have been used for this test.

▲	GD/GSC	Standard model
■	VL-D	Lamont - Doherty Geological Observatory model
◫	VSO	Model suggested for southern Ontario in this study

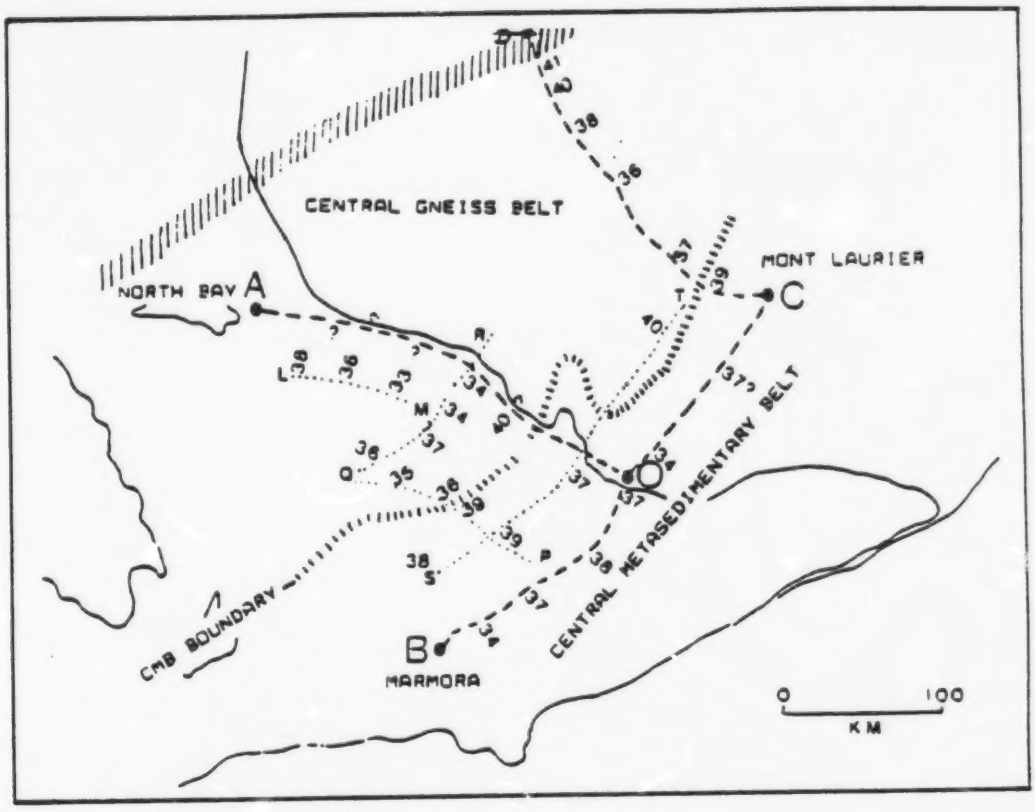


FIGURE 2.7: Map showing shot points and seismic lines for the 1982 COCRUST seismic experiment. Depths to the MOHO along the lines of study are also shown
(after Mereu et al 1986)

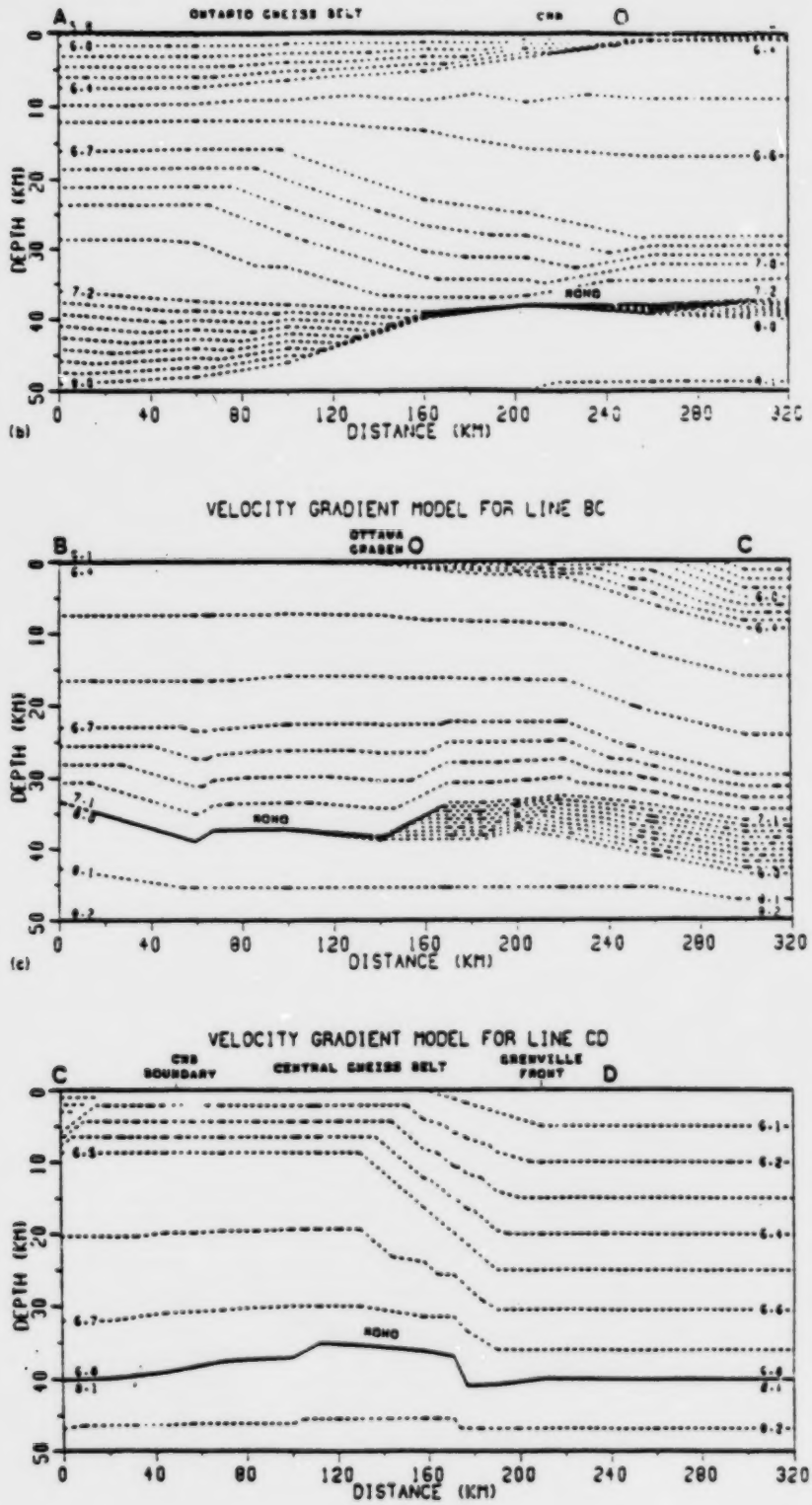


Figure 2.8: Crustal velocity profiles along the 1982 seismic experiment lines (figure 2.7) derived from synthetic seismogram analysis (after Mereu, et al., 1986).

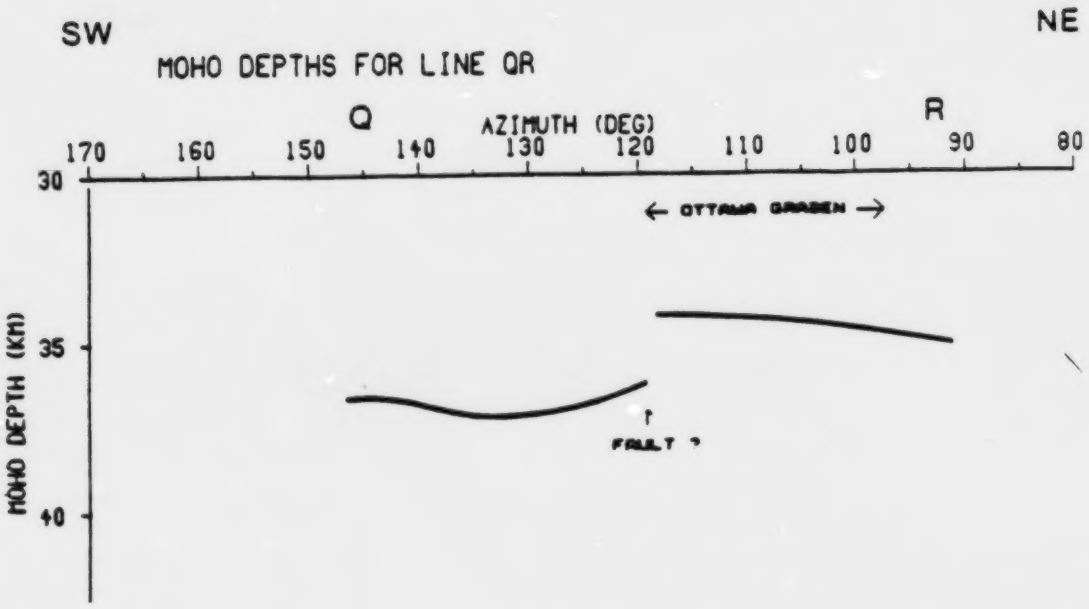


Figure 2.9: Moho depth profile across the Ottawa-Bonnechere Graben, showing a major displacement along a vertical fault. The angular distances are measurements of azimuth from A shown in Figure 2.7 (after Mereu et al., 1986).

2.3 Current Detection Threshold in Southern Ontario

The present relative detection and location capability for events in southern Ontario may be considered by using the relationship between magnitude distance trace amplitude as recorded in local seismographic stations. The formula suggested by Nuttli (1973) for determination of equivalent m_b magnitudes of earthquakes in eastern North America, which is based on the amplitude of short-period Rayleigh waves in medium range distances, has been adopted for this purpose.

For epicentral distance (^) ranging from 0.5 to 4 degrees, the formula takes the following constants,

$$m_b(M_n) = 3.75 + 0.90(\log \text{^}) + \log A/T$$

where A is zero to peak ground motion in microns and T the period in seconds.

According to the Canadian Seismographic Operation report (Munro et al., 1984) a peak to peak trace amplitude of 4 millimeters is a usual routine to depict and report phases for location and magnitude calculations. The instrument magnification factors at 5 Hz (dominant frequency for local Lg waves observed by Chun et al., 1987), were used to estimate the maximum distances that magnitude 3 and 2.5 events can be normally detected by each station.

The results shown in Figures 2.10 and 2.11, illustrate the limited area of full coverage between at least three stations to make the location of magnitude 3 events possible. For magnitude 2.5 events, however, no three station overlap exists in southern Ontario. This would imply that magnitudes less than 3 may be recorded by one or two stations but they may not be locatable with a reasonable accuracy in this region.

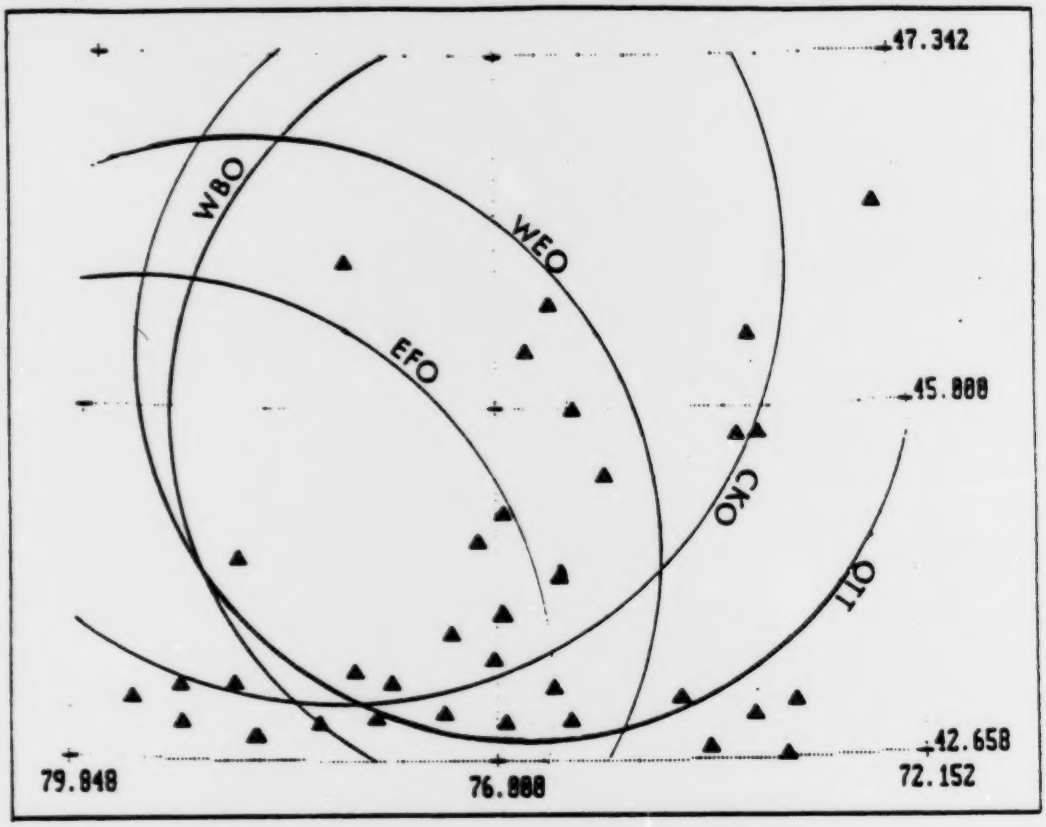


Figure 2.10: Detection threshold for magnitude 3 events by the Canadian seismographic stations in southern Ontario.

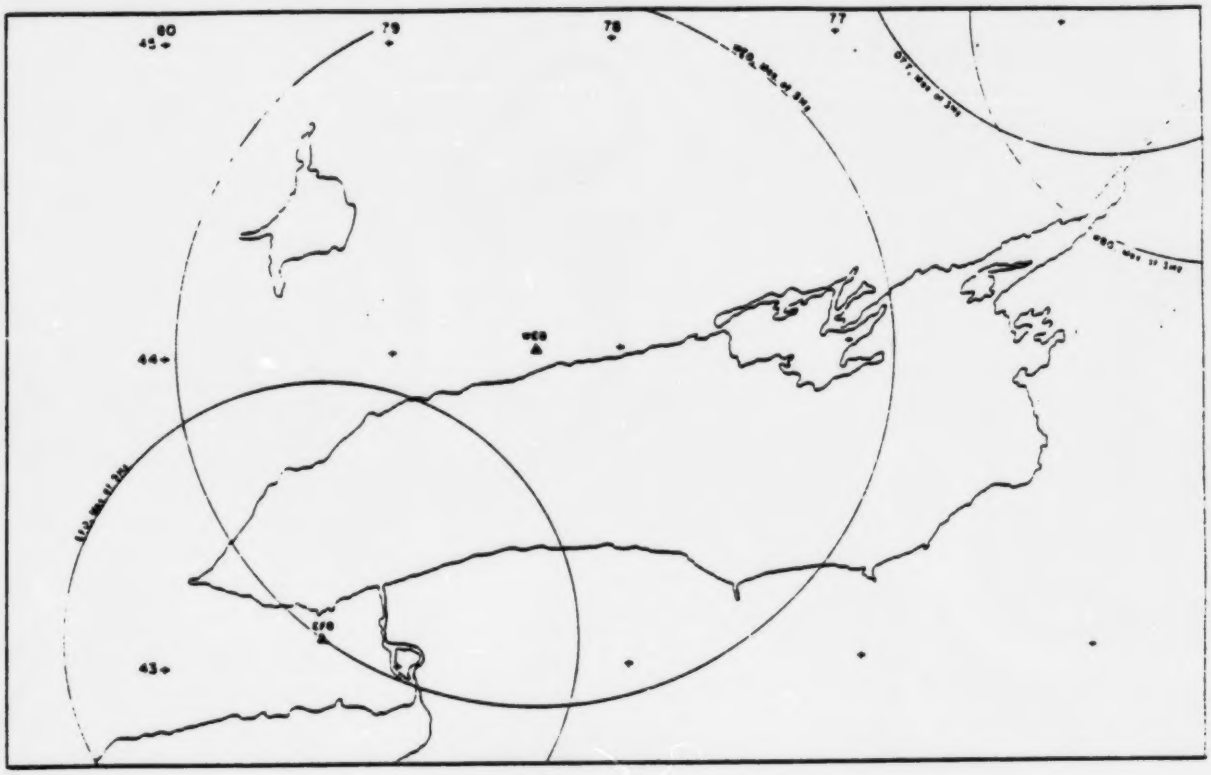


FIGURE 2.11: Detection threshold for earthquakes of MbLg ≈2.5 at 5Hz in Southern Ontario

3 RELOCATION OF THE EARTHQUAKES

Routinely determined epicenters in the Western Quebec Seismic Zone (WQSZ) as defined by Basham et al. (1979; 1982), show a diffuse pattern of seismicity (Figure 2.1; 3.1). Earthquake distributions in southern Ontario tend to be even more disperse (Figure 3.2). Mislocation errors for earthquakes in the study region may be considered to be a contributing cause of the apparent diffuse seismicity pattern which has been discussed in section 2.1.

An attempt has been made to test the suitability of the Joint Hypocenter Determination (JHD) of Douglas (1967), Dewey (1971) and single event location of Dewey (1979), also the most up-to-date local earthquake location code "HYPOCENTER" (Linert, 1986) for improving the location accuracy of earthquakes in the WQSZ and southern Ontario.

3.1 The Input Data File

The available files of the Geophysics Division (formerly Earth Physics Branch, EPB) of the GSC, and the Lamont-Doherty Geological Observatory of Columbia University were scrutinized to select events which could match the requirements of the above codes and with sufficient phase readings to provide stable solutions for the results in the recomputation of locations. Phase arrival data for the seismic events in these regions prior to 1970 were collected from the bulletins of the International Seismological Centre (ISC), and the available files of the GD/GSC (Lamontagne and Plouffe, personal communication). For events between 1978 to 1987 the Pik File computer tape of the GD/GSC was used (Wetmiller, personal communication).

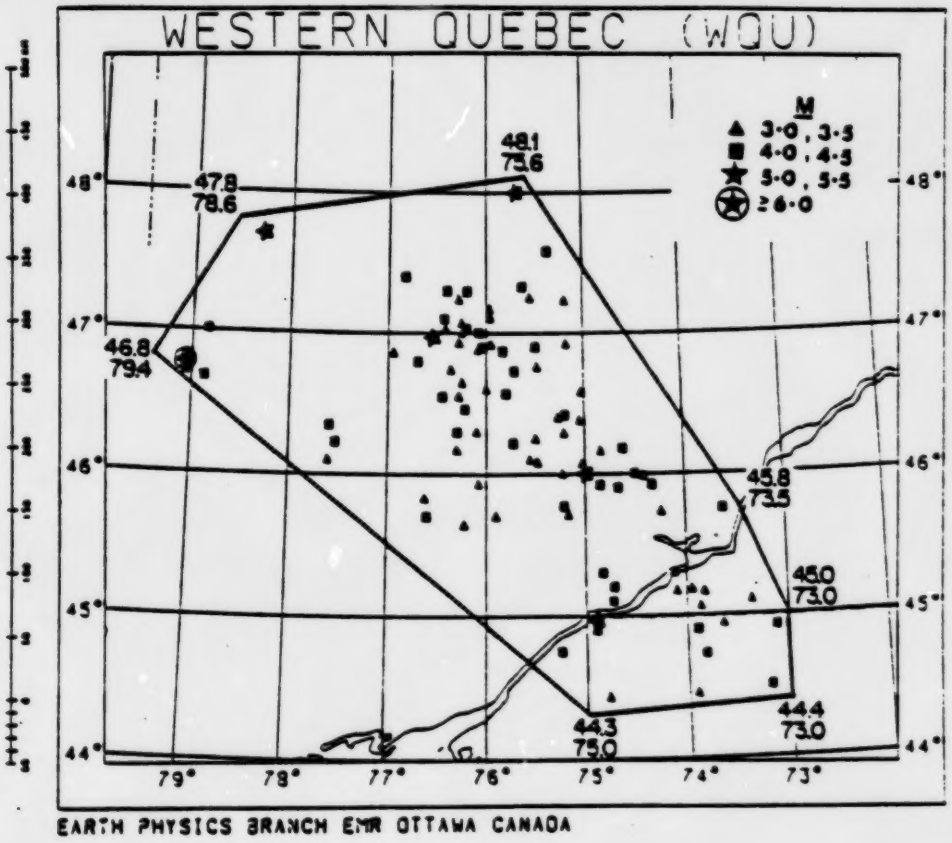


Figure 3.1: Map showing boundaries of the Western Quebec Seismic Zone (WQSZ) as defined by Basham et al. (1982, 1985).

This file contains the Observed Data Record (ODR) of all the readable phases, Earthquake Comment Record (ECR) in addition to the Earthquake Solution Record (ESR), and calculated data record (CDR) which are the output files from the CANSESS MULTI-LAYER epicentre location program currently used by the GD/GSC for routine computation of earthquakes in Canada. The ODR file lists the Pn, Pg, Sn, and Lg arrivals with a varying quality designator namely: sharp clear beginning (A, +/- 0.25 sec), good beginning (B, +/- 1.0 sec) and weak to poor beginning (C, +/- 4 sec or more).

As concluded in the error sensitivity analysis in section 2, care has been taken to use only quality A and B phase readings for most of the relocated events. This has been one of the main constraints in the data search which has placed a significant limitation on the number of relocatable earthquakes. Further data retrieval procedure entails a re-examination and re-reading of the original records which may improve consistency and ultimately the quality of input data. Such a task, which is recommended as necessary for site specific studies, is beyond the scope of the present report.

3.2 Joint Epicentre/Hypocentre Determination (JED/JHD)

The Joint Epicentre Determination (JED) is a method of determining station travel time corrections and the positions and origin times of more than one earthquake simultaneously which was originally proposed by Douglas (1967) and slightly modified Joint Hypocentre Determination (JHD) and extensively utilized by Dewey (1971; 1979) and Dewey and Gordon (1984). This method can provide significant improvement over conventional single event location methods if the systematic travel-time anomalies are large compared to random errors and all the anomalies along the ray path can be considered mathematically as station effects. The JHD method is insensitive to the crustal velocity models and uses travel time residuals as station adjustments for refining the location of regional and teleseismic events. JED/JHD has been very successful in reducing the error type due to station biasing associated with different combinations of stations used in earthquake location routines (Dewey and Algermissen, 1974; Dewey, 1979).

From past experience, it has been observed that the calculated locations are more reliable and hence, more stable if a calibration or master event is used. The JHD method can be used successfully if the following criteria are met:

1) The calibration event must be constrained to a well-located correct hypocentre or all other locations determined in the run will be biased and offset by the same amount.

2) It is important that the ray paths of the events to be relocated are roughly similar to those of the calibration event.

3) Sufficient azimuthal and distance coverages are important to obtain stable solutions.

If these conditions can be satisfied, then the travel time anomalies can be applied as station corrections and the error in positioning of the calibration event relative to the other events in the run will be reduced. The amount and stability of this reduction depends on azimuthal and distance coverage of the recording stations. Because JHD is not sensitive to the crustal velocity models, this method is capable of generating the most accurate earthquake locations under the above conditions.

The largest and closest event to the study area that fulfills these criteria is the magnitude 5.1 mb event which occured on October 7_{th}, 1983 near Goodnow N.Y. The event was adopted as the calibration event for the following reasons :

- Accurate locations of the hypocentre with relatively small deviations were available from several organizations.

- This event was chosen to test the reliability of the method when used jointly with another well-studied event such as the North Gower, Ontario earthquake of October 11, 1983 (Wahlstrom, 1987).

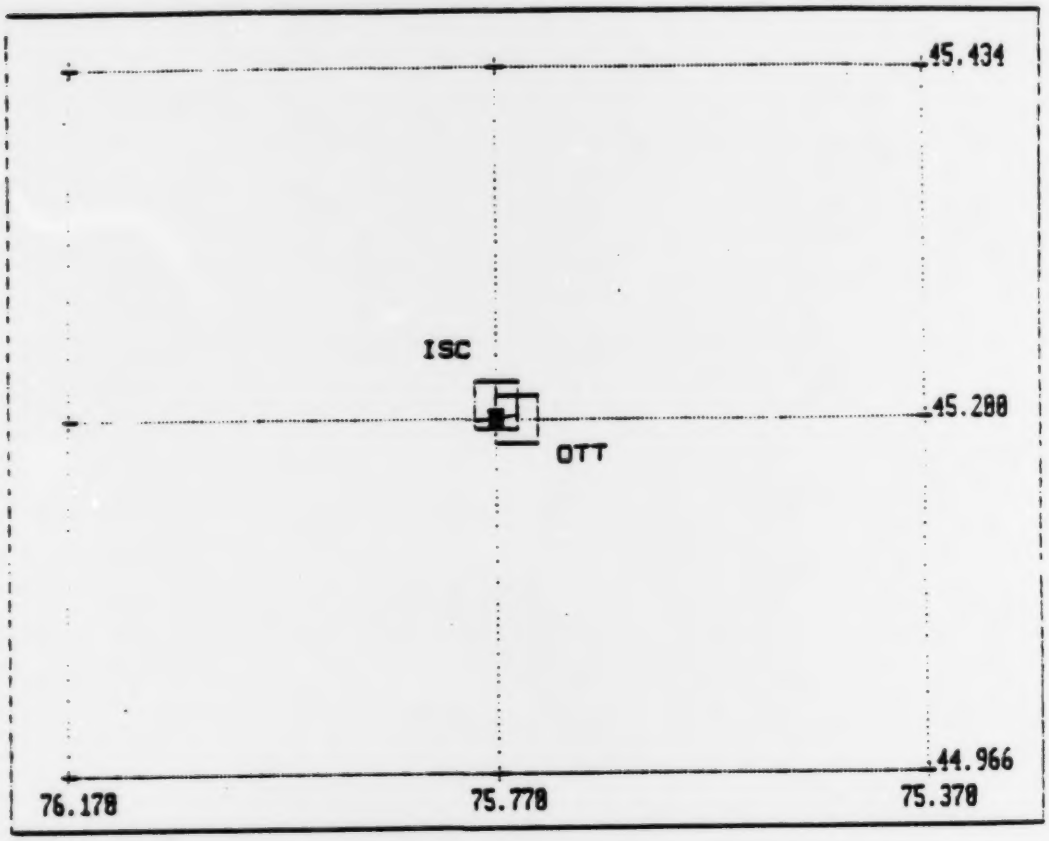
The L-DGO solution for the October 7, 1983 earthquake was adopted as the master (calibration) location in the first step of the study. Twenty events with magnitude greater than 3.4, which have occurred in the study region since 1978, were chosen to be analysed jointly with the 1983 Goodnow event. A final combination of 5 events was

found to be the maximum number of events which could be run together, while presenting adequate station coverage. The number of events was restricted to 5 because of the following limitations; a) Events with moderately low magnitudes (3.5 - 4.0) within the study region were recorded by limited number of stations. Many of the events (11) were recorded before 1982, prior to the operation of several of the seismographic stations now in the study area, b) Due to the separation of the Goodnow event from southern Ontario region and that the lower magnitude events in the study area had not been adequately recorded by American stations, therefore, very few events have common station readings with the selected master event. The results for the first test run of four events in southern Ontario and western Quebec relocated jointly with the October 7, 1983 Goodnow earthquake, serving as a master event, is given in Table 3.1. A summary of the results of the first step relocations as compared with the GD/GSC determinations are presented in Figures 3.2 to 3.5.

The errors given for each location by a 90% confidence ellipse do not exceed 6 Km in the major axis and on average are slightly greater than 4.3 Km. The variation of the observed travel times from the calculated travel time is less than 0.11 seconds which is adequately low. The error which can be assigned to the relative positions of the events within the run is less than 5 km. The error in the spatial distribution of the group of epicenters is dependent on the location of the master event which is also likely to be less than 5 Km.

The depth of the epicenters were held at values determined by the GD/GSC since no $_pP$ phases were available and the data set was not large enough to determine stable depths. Adjusted depths of the epicenters in the run had no significant effect on the location of the epicenters and affected only the origin times.

With locations of these four larger events more confidently known within the study region, other events were selected for the second step of the relocation procedure, utilizing JHD with the above four earthquakes (Table 3.1) as secondary calibration events. Examples of another test combination of events relocated jointly with the North Gower earthquake of October 11, 1983 are given in Table 3.2.



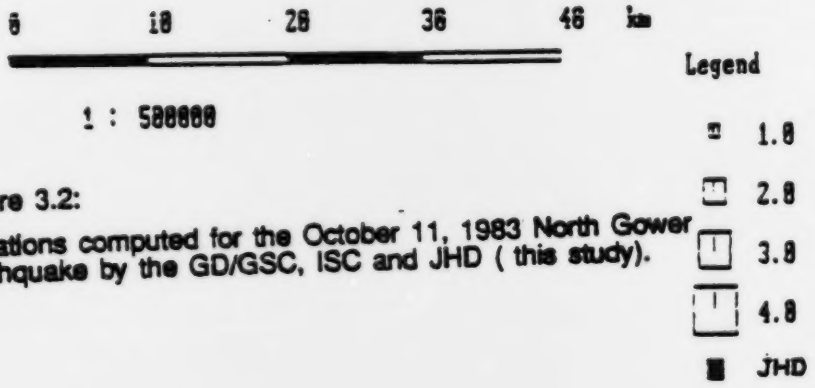


Figure 3.2:
Locations computed for the October 11, 1983 North Gower earthquake by the GD/GSC, ISC and JHD (this study).

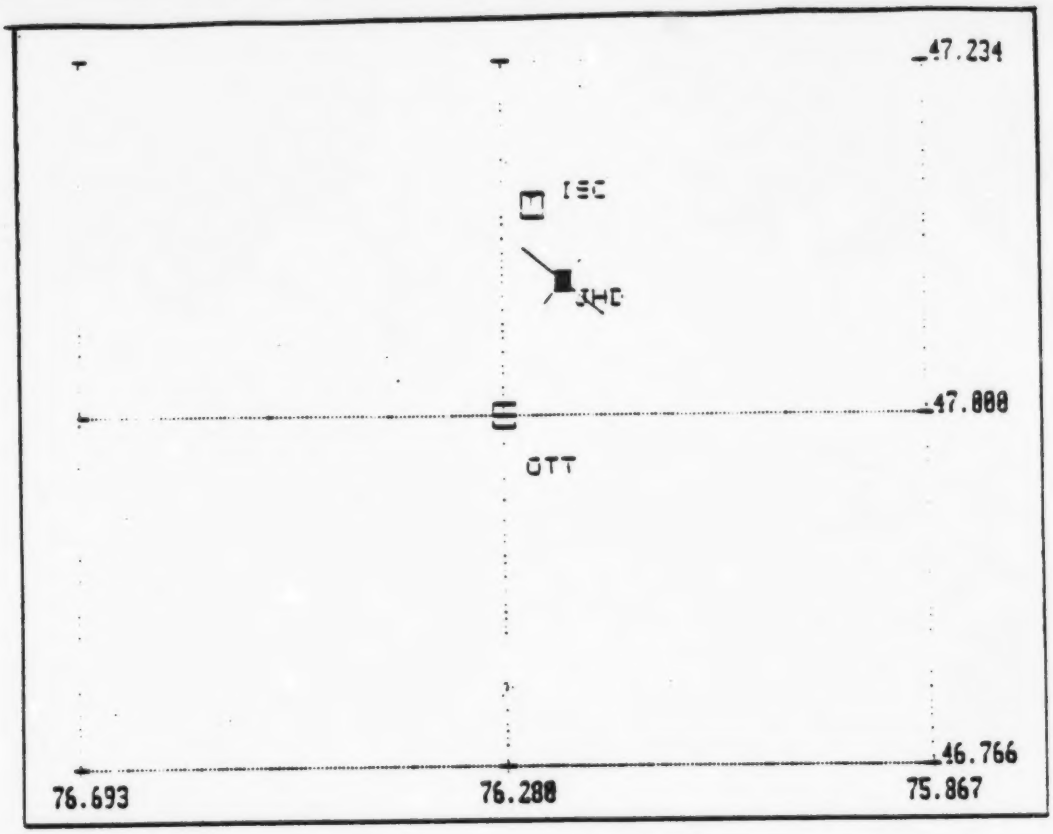
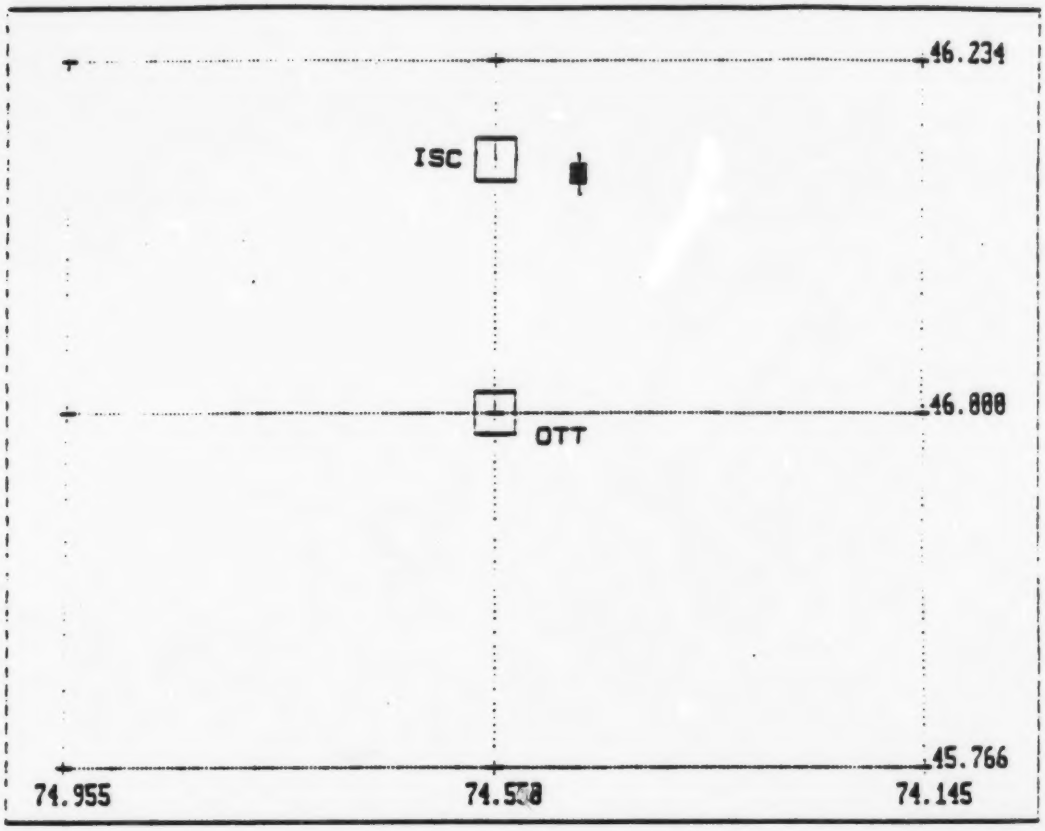


Figure 3.3:

Locations computed for the December 28, 1982 earthquake by the GD/GSC, ISC and JHD (this study, with the 90% confidence error bar).



0 10 20 30 40 km

1 : 500000

Legend

1.0
2.0
3.0
4.0
JHD

Figure 3.4:

Locations computed for the July 13, 1982 earthquake by the GD/GSC, ISC and JHD (this study, with the 90% confidence error bars).

Lambert Conformal Projection Files: ont.eq
reloc.epi

Table 3.1: The first step JHD test run. The Goodnow, N.Y earthquake of 7 October 1983 is considered as the master event in this run.

ORIGINAL EPICENTER LOCATIONS:

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME	MAGNITUDE
19831007	43.94	74.25	10.12	10.00 18.00 46.26	5.1
19831011	45.20	75.75	13.00	4.00 10.00 55.00	4.1
19831228	47.00	76.28	17.00	12.00 24.00 22.00	3.5
19820713	46.00	74.55	18.00	2.00 18.00 49.00	3.8
19820806	45.80	75.46	18.00	6.00 29.00 10.00	3.7

RESULTANT EPICENTER LOCATIONS:

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19831007	43.94	74.25	10.12	10.00 18.00 46.26

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
WBO	1.29	325.67	0.20	-0.64	1.73
VDQ	5.01	330.20	0.01	-0.87	1.74
GAC	1.97	334.06	0.52	-0.80	1.70
OTT	1.79	324.78	0.60	-0.88	1.67
GNT	2.76	28.08	-0.34	-0.12	1.72
WEO	2.98	267.07	-0.48	-0.43	1.70
MNT	1.62	15.75	-0.13	-0.52	1.73
SBQ	2.19	48.25	0.24	-0.10	1.73
LPQ	4.52	39.68	-0.25	0.15	1.73
MNQ	7.57	27.52	-0.34	-1.59	1.72

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19831011	45.20	75.77	13.00	4.00 10.00 55.55

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
WBO	0.40	119.85	-0.52	-0.64	1.53
VDQ	3.39	334.19	0.18	-0.87	1.56
GAC	0.54	21.85	-0.13	-0.80	1.57
OTT	0.20	169.63	-0.68	-0.88	1.49
GNT	2.64	62.73	0.04	-0.12	1.57
WEO	2.21	238.51	0.04	-0.43	1.57
MNT	1.54	77.98	0.48	-0.52	1.54
SBQ	2.72	84.90	0.12	-0.10	1.57
LPQ	4.53	59.76	-0.17	0.15	1.56
MNQ	7.11	38.88	0.63	-1.59	1.50

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19831228	47.04	76.24	17.00	12.00 24.00 23.76

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
WBO	2.15	161.34	-0.74	-0.[illegible]4	0.51
VDQ	1.67	316.23	-0.32	-0.8[illegible]	0.55
GAC	1.44	158.08	0.05	-0.80	0.55
OTT	1.68	167.26	-0.01	-0.88	0.55

GNT	2.75	102.80	-1.41	-0.12	0.08
WEO	3.37	207.16	1.27	-0.43	0.18
MNT	2.38	129.24	-0.75	-0.52	0.51
SBQ	3.43	117.40	1.17	-0.10	0.27
LPQ	4.26	83.63	0.97	0.15	0.43
MNQ	6.05	51.92	0.00	-1.59	0.55

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19820713	46.07	74.53	18.00	2.00 18.00 49.34

STATION	DELTA(DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
WBO	1.19	206.43	0.36	-0.64	0.90
VDQ	3.19	313.92	-0.78	-0.87	0.83
GAC	0.75	241.65	-0.32	-0.80	0.90
OTT	1.07	231.45	0.23	-0.88	0.90
GNT	1.53	78.00	0.41	-0.12	0.89
WEO	3.41	234.46	0.45	-0.43	0.89
MNT	0.85	131.24	-0.47	-0.52	0.89
SBQ	1.95	109.71	-0.80	-0.10	0.82
LPQ	3.36	66.08	0.49	0.15	0.89
MNQ	5.89	38.57	0.29	-1.59	0.90

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19820806	45.80	75.40	18.00	6.00 29.00 11.79

STATION	DELTA(DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
WBO	0.80	173.60	0.56	-0.64	1.00
VDQ	3.00	325.06	0.80	-0.87	0.93
GAC	0.11	209.93	-0.33	-0.80	1.02
OTT	0.46	208.78	-0.19	-0.88	1.02
GNT	2.18	73.92	0.28	-0.12	1.02
WEO	2.76	230.95	-0.26	-0.43	1.02
MNT	1.28	102.71	0.43	-0.52	1.01
SBQ	2.48	98.52	-0.16	-0.10	1.02
LPQ	4.03	65.53	-0.27	0.15	1.02
MNQ	6.49	40.69	-0.84	-1.59	0.91

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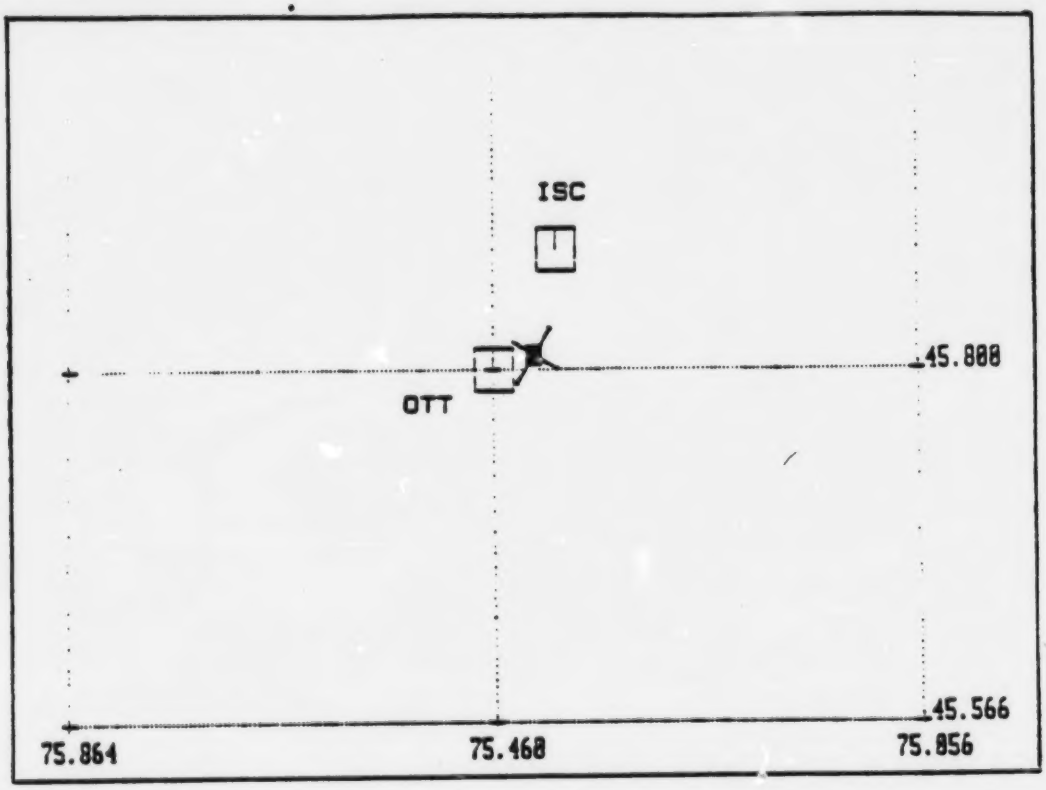
90 PER-CENT CONFIDENCE ELLIPSES FOR EPICENTERS

ALPHA = ANGLE OF AAX SEMI-AXIS MEASURED COUNTER-CLOCKWISE FROM EAST

19831011	2ALPHA =	13.41712	AAX =	3.07287	BAX =	2.45428
19831228	3ALPHA =	-17.56671	AAX =	5.84058	BAX =	4.25726
19820713	4ALPHA =	65.62498	AAX =	4.31174	BAX =	2.55868
19820806	5ALPHA =	48.73018	AAX =	4.23189	BAX =	2.62841



1 : 500000

Legend

1.0
2.0
3.0
4.0
JHD

Figure 3.5:

Locations computed for the August 6, 1982 earthquake by the GD/GSC, ISC and JHD (this study with the 90% confidence error bars).

Lambert Conformal Projection Files: ont.eq
reloc.epi
stat.cor

Table 3.2: The second stage JHD test run. The North Gower earthquake of 11 October 1983 is considered as the master event in this run.

ORIGINAL EPICENTER LOCATIONS:

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME	MAGNITUDE
19831011	45.20	75.77	13.00	4.00 10.00 55.50	4.1
19831228	47.00	76.28	17.00	12.00 24.00 22.00	3.5
19820903	45.60	76.58	18.00	23.00 14.00 3.00	3.7
19820813	46.60	78.53	18.00	1.00 6.00 42.00	4.3
19820806	45.80	75.46	18.00	6.00 29.00 10.00	3.7
19820713	46.00	74.55	18.00	2.00 18.00 49.00	3.8

RESULTANT EPICENTER AND STN NUMBERS:

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19831011	45.20	75.77	13.00	4.00 10.00 55.50

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
SBQ	2.72	84.88	-0.07	0.11	1.97
MNT	1.54	77.94	0.49	-0.53	1.96
WEO	2.20	238.50	0.02	-0.31	1.97
WBO	0.40	119.50	-0.21	-0.92	1.97
OTT	0.20	11.12	-0.34	-1.20	1.97
GAC	0.54	22.09	0.43	-1.34	1.96
VDQ	3.39	334.24	-0.30	-0.35	1.97

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19831228	47.09	76.22	17.00	12.00 24.00 23.48

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
SBQ	3.43	118.34	1.11	0.11	0.44
MNT	2.40	130.51	-0.75	-0.53	0.48
WEO	3.43	207.04	0.66	-0.31	0.48
WBO	2.19	162.24	-0.80	-0.92	0.47
OTT	1.73	168.24	-0.17	-1.20	0.49
GAC	1.48	159.52	0.19	-1.34	0.49
VDQ	1.65	314.50	-0.18	-0.35	0.49

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19820903	45.64	76.57	18.00	23.00 14.00 3.94

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
SBQ	3.28	92.89	2.53	0.11	0.00
MNT	2.07	92.67	-0.76	-0.53	0.71
WEO	2.07	219.06	-0.26	-0.31	0.73
WBO	1.11	124.42	0.88	-0.92	0.70
OTT	0.65	111.74	-0.15	-1.20	0.73
GAC	0.77	95.36	-0.07	-1.34	0.73
VDQ	2.77	340.19	0.27	-0.35	0.73

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19820813	46.62	78.65	18.00	1.00 6.00 41.34

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
SBQ	4.85	102.44	-0.56	0.11	1.30
MNT	3.68	105.93	0.66	-0.53	1.29
WEO	2.61	175.58	0.04	-0.31	1.32
WBO	2.87	123.27	-0.34	-0.92	1.31
OTT	2.39	119.92	3.40	-1.20	0.00
GAC	2.39	111.49	0.20	-1.34	1.31
VDQ	1.67	15.80	-0.01	-0.35	1.32

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19820806	45.81	75.42	18.00	6.00 29.00 11.85

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
SBQ	2.49	98.64	-0.61	0.11	0.69
MNT	1.30	102.91	0.17	-0.53	0.70
WEO	2.76	230.64	-0.86	-0.31	0.67
WBO	0.81	172.75	0.66	-0.92	0.69
OTT	0.46	206.88	0.06	-1.20	0.70
GAC	0.11	201.97	0.14	-1.34	0.70
VDQ	2.99	325.17	0.41	-0.35	0.70

EARTHQ	LATITUDE	LONGITUDE	DEPTH	ORIGIN TIME
19820713	46.16	74.47	18.00	2.00 18.00 48.44

STATION	DELTA (DEG)	AZIMUTH	RESIDUAL	STNADJ	WEIGHTING
SBQ	1.94	112.69	0.02	0.11	90.23
MNT	0.88	137.56	-0.02	-0.53	90.23
WEO	3.50	233.71	0.03	-0.31	90.23
WBO	1.29	206.41	0.01	-0.92	90.23
OTT	1.16	229.34	0.05	-1.20	90.23
GAC	0.84	237.68	-0.08	-1.34	90.22
VDQ	3.16	312.25	0.00	-0.35	90.23

---

90 PER-CENT CONFIDENCE ELLIPSES FOR EPICENTERS

ALPHA = ANGLE OF AAX SEMI-AXIS MEASURED COUNTER-CLOCKWISE FROM EAST

19831228	2ALPHA =	-41.44588	AAX =	8.35790	BAX =	4.63009
19820903	3ALPHA =	97.59910	AAX =	5.50254	BAX =	4.05574
19820813	4ALPHA =	2.83238	AAX =	6.36800	BAX =	3.81283
19820806	5ALPHA =	69.62337	AAX =	4.81431	BAX =	3.93876
19820713	6ALPHA =	96.55150	AAX =	2.96728	BAX =	1.60192

Results from several test runs show that the JHD method can confidently improve the location of those events which have a well-recorded data base and which also have a near complete azimuthal coverage by regional seismographic stations. The effect of JHD on locally recorded data in the study area is not as certain as for the larger events with regional phase data. Similar limitations were encountered by Viret et al., (1984) when the JHD method was used for relocation of the locally recorded earthquakes in Virginia. Thus, combinations of 67 earthquakes within the study area recorded on regional stations and for which there are sufficient input data to give stable solutions through the JHD program have been tabulated and compared with GD/GSC locations in Table 3.3. A plot of the relocated earthquakes is presented in Figure 3.5, with corresponding error bars for each epicentre designating the semi-major and semi-minor axes of the 90% confidence error ellipse.

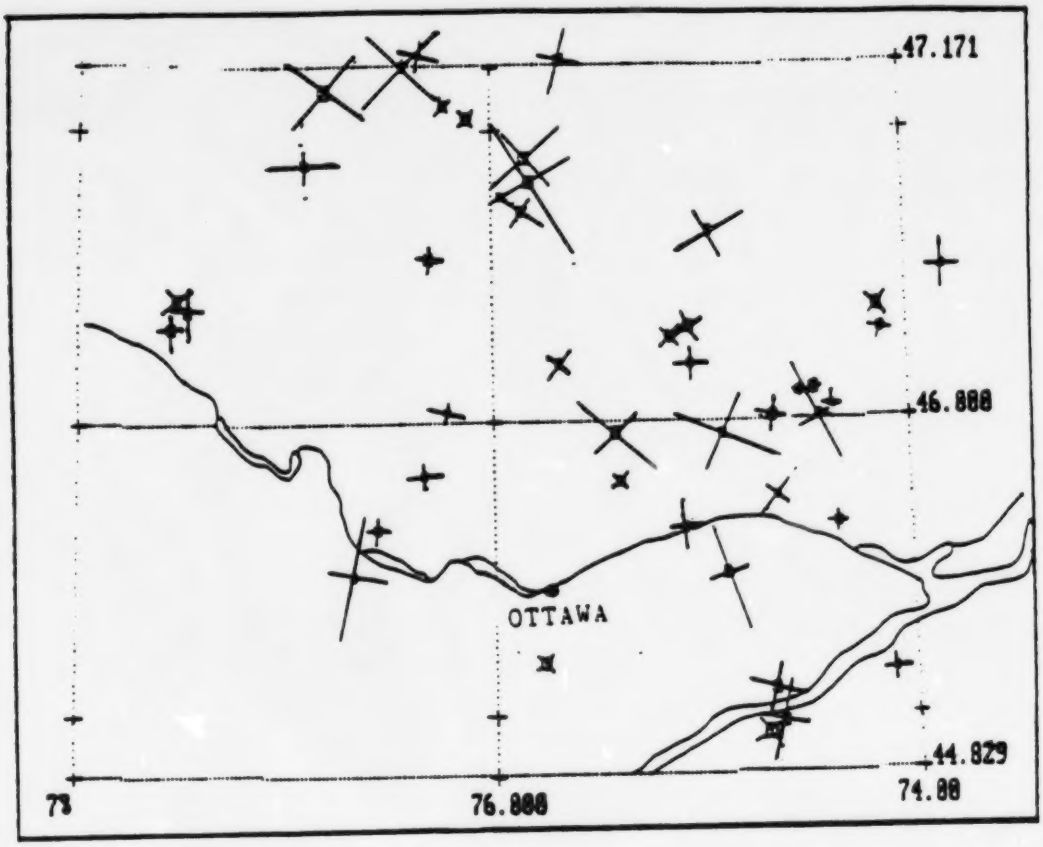
TABLE 3.3. RELOCATED HYPOCENTERS IN SOUTHERN ONTARIO AND WESTERN QUEBEC USING JHD CODE

DATE	O.T	LAT(N)	LONG(W)	FD	MAG		90% CONFIDENCE ELLIPSE		
yr mo dy	h m s	deg	deg	km	mbLg (Mn)		Az(maj) deg	Lmaj km	Lmin km
19290812	112448.7	42.91	78.40	8.9	5.2		97.3	19.8	15.1
--------	------.0	42.87	78.35		5.5	ML EPB			
19310420	195430.6	43.47	73.79	5.0*	4.7		-145.3	18.7	12.8
--------	----00.0	43.4	73.7		4.5	ML EPB			
19351101	6 334.2	46.87	79.05	1.0*	6.2		143.0	12.5	10.1
--------	--300.0	46.78	79.07		6.2	ML EPB			
19371106	143120.6	46.79	75.82	24.2	4.0		150.8	40.7	22.8
--------	------.9	46.73	75.72		4.0	ML EPB			
19371112	144342.4	46.01	74.45	5.0*			148.8	19.9	10.5
--------	-----4.3	45.92	73.33		3.6	ML EPB			
19371112	165731.3	46.10	74.47	1.0*	4.0		147.7	20.6	10.6
--------	-----2.5	45.92	74.33		3.7	ML EPB			
19430706	221016.0	44.84	73.03	22.4	4.0		80.8	15.9	10.3
--------	-----4.8	44.92	73.13		4.1	ML EPB			
19440905	43845.7	44.96	74.72	11.5	5.8		55.9	10.0	9.5
--------	------.0	44.97	74.90		5.6	ML EPB			
19440905	851 6.0	45.00	74.65	1.0*	4.5		-167.1	18.2	12.5
--------	--------	44.98	74.90		4.6	ML EPB			
19440909	232450.3	45.11	74.69	1.0*	4.0		-165.2	13.3	10.4
--------	----48.0	44.98	74.90		4.1	ML EPB			
19480507	12 227.3	45.86	73.69	3.2	4.0		143.0	17.8	9.6
--------	-----6.0	45.75	73.63		4.0	ML EPB			
19491016	233345.4	45.49	74.90	14.1	4.0		149.1	68.6	10.3
--------	-----2.3	45.30	74.83		4.2	ML EPB			
19511106	175445.9	44.92	73.55	30.9	4.1		72.3	14.5	10.7
--------	-----1.5	45.00	73.5		3.7	ML EPB			
19520719	11617.2	46.87	75.84	1.0*	4.5		46.5	18.7	13.9
--------	------.0	46.87	75.83		4.3	ML EPB			
19530331	125833.4	43.77	73.08	1.0*	4.0		63.8	17.5	8.6
--------	-----4.3	44.07	73.12		4.0	ML EPB			

19540412	212200.1	47.00	76.12	6.1	4.5		155.9	17.6	13.7
--------	-----1.0	46.90	76.05		4.3	ML	EPB		
19540911	185555.6	47.19	75.66	27.9	4.5		-170.5	17.7	9.5
--------	------.2	47.33	75.63		4.6	ML	EPB		
19561104	115329.2	45.96	75.42	1.0*	4.0		130.2	19.5	10.3
--------	-----4.0	46.22	75.73		4.0	ML	EPB		
19580514	174116.7	47.09	76.82	1.0*	5.0		127.8	17.3	16.6
--------	----21.0	46.97	76.55		5.0	ML	EPB		
19610306	121329.3	48.11	79.97	1.0*			-151.8	15.2	5.4
--------	-----8.0	48.15	80.03	1.1	4.8	ML	EPB ROCKBURST		
19620410	143045.2	44.11	72.97	4.7	4.2		109.2	11.1	8.3
--------	-----8.0	44.15	73.05		4.3		EPB		
19631015	1229 0.0	46.31	77.55	5.0*	4.0		-174.9	11.4	5.1
--------	-----2.0	46.17	77.59		4.1		EPB		
19631015	135950.8	46.37	77.47	8.2	4.0		-176.8	13.1	5.9
--------	-----3.0	46.18	77.59		4.2		EPB		
19640108	10 430.3	46.41	77.53	21.4	4.3		47.8	8.8	6.9
--------	-- --1.0	46.23	77.53		3.8	Mb	EPB		
19651107	205741.8	47.25	76.36	9.5	4.0		105.8	6.8	6.7
--------	-----4.0	47.10	76.06		4.2		EPB		
19660101	132339.0	42.84	78.25	5.0*	4.6		163.8	5.2	4.6
--------	-----8.0	42.90	78.20	10.0	4.7	Mb	EPB		
19670613	19 855.5	42.84	78.23	1.0*	4.4		177.9	5.2	4.9
--------	-----4.0	42.90	78.20		4.5		EPB		
19691010	000704.9	46.31	75.06	2.1	4.5		167.3	5.9	5.8
--------	-----7.0	46.42	75.20	18G	4.2		EPB		
19710523	62427.9	43.90	74.48	8.8	4.1		106.7	4.2	4.6
--------	-----.0	43.82	74.54	1G	3.7		EPB		
19710523	92959.5	43.93	74.47	1.0	3.8		101.5	4.2	3.9
--------	-----.0	43.94	74.55	00G	3.6		EPB		
19710621	24831.6	43.90	74.48	1.5	3.4		82.2	7.9	5.1
-------	----4.0	43.99	74.53	1G	3.3		EPB		
19710710	815 1.5	43.91	74.44	1.7	3.6		99.2	6.1	4.3
--------	--- 2.0	43.93	74.53	1G	3.4		EPB		
19711218	153624.5	46.01	74.67	12.9	4.0		172.1	7.4	5.1
--------	------.0	46.18	74.62	18G	3.9		EPB		

19721216	190137.2	45.64	75.10	9.7	3.9	165.5	9.9	4.2
	-----6.0	45.79	75.21	18G	3.9	EPB		
19730715	82030.7	43.89	74.43	0.5	3.5	83.2	4.3	3.5
	----1.0	43.97	74.49	18G	3.4	EPB		
19730715	103237.8	43.92	74.40	3.4	3.2	72.9	4.2	3.1
	-----8.0	43.96	74.43	18G	3.2	EPB		
19750609	183922.7	44.87	73.65	11.4	3.5	107.6	3.9	3.1
	------.0	44.94	73.65	10 G	3.5	EPB		
19750712	123713.8	46.54	76.31	8.8	4.3	-156.9	5.4	4.3
	-----5.0	46.46	76.28	17	4.1	EPB		
19750821	214252.1	48.20	77.87	14.2	3.5	165.2	18.8	15.5
	-----1.0	48.16	78.01		3.6	EPB		
19751103	205455.3	43.91	74.65	4.8	4.0	52.2	3.5	3.0
	------.0	43.91	74.64	3	4.1	LDGO		
19751219	152511.0	47.01	78.89	14.0	3.6	178.1	13.4	7.1
	-----	47.01	78.84	18G	3.8	EPB		
19760713	35113.3	45.16	74.12	3.2	3.1	171.1	4.4	3.2
	-----4.0	45.17	74.10	9.0	3.1	EPB		
19770714	73929.8	46.04	74.39	3.5	3.8	-160.3	6.3	4.0
	----30.0	45.98	74.41	18G	3.4	EPB		
19771016	212919.1	46.52	73.82	0.7	3.0	-176.2	8.9	5.3
	------.0	46.58	73.68	18G	3.0	EPB		
19771107	204852.7	46.28	75.15	4.7	3.0	-156.8	6.4	4.3
	------.0	46.29	75.21	18G	3.0	EPB		
19771125	184724.4	46.69	75.86	1.0*	3.0	128.2	16.2	7.8
	-----2.0	46.74	76.36	18G	3.0	EPB		
19771222	1457 1.3	46.84	76.91	10.6	3.5	84.9	33.3	27.1
	-----0.0	46.86	76.94	18G	3.5	EPB		
19780218	144824.3	46.37	74.15	1.8	4.1	-156.8	5.5	4.1
	-----5.0	46.35	74.11	7G	4.1	EPB		
19780223	52432.3	46.29	74.14	1.0	3.4	-170.9	5.4	4.5
	----3.0	46.36	74.13	7.0	3.4	EPB		
19780730	105443.7	45.65	74.37	7.1	3.6	174.8	4.4	3.1
	-----4.0	45.68	74.44	18G	3.6	EPB		
19780826	35434.1	47.17	76.43	5.4	3.0	-145.9	25.3	24.1
	----3.0	47.14	76.53	18G	3.0	EPB		

19790318	163114.0	45.82	76.34	1.0*	3.0	83.2	7.8	4.2
--------	-----2.0	45.84	76.43	18G	3.0	EPB		
19790526	215832.8	46.19	75.68	1.0*	3.3	-144.2	8.1	5.2
--------	-----0.0	46.34	75.68	1.0	3.3	EPB		
19800124	54447.0	46.19	75.06	5.0	3.2	-174.2	8.0	6.1
--------	----9.0	46.14	75.07	5.0	2.6	EPB		
19800606	131552.9	43.57	75.14	1.0*	3.5	78.2	5.1	4.1
--------	------.0	43.66	75.14	0.0	3.5	EPB		
19801014	05856.4	43.15	80.57	4.6	3.5	178.9	10.8	3.2
--------	----7.0	43.12	80.56	18G	3.5	EPB		
19820713	021849.3	46.09	74.54	11	3.8	25.0	4.9	2.6
--------	------.0	46.00	74.55	18	3.8	EPB		
19820806	062911.8	45.80	75.40	7	3.7	40.9	4.6	2.8
-------	-----0.0	45.89	75.46	18	3.7	EPB		
19820813	010641.3	46.62	78.65	18	4.3	86.8	5.9	4.1
--------	-----2.0	46.66	78.61	18	4.3	EPB		
19820903	231403.9	45.64	76.57	13	3.7	3.9	5.0	3.8
--------	------.0	45.69	76.61	18	3.7	EPB		
19830717	224741.9	46.02	74.95	14	3.0	55.0	3.2	2.1
--------	-----	46.06	74.90	14	3.0	EPB		
19831007	101846.2	43.94	74.25	10	5.1	MASTER EVENT # 1		
19831011	041055.5	45.20	75.77	13	4.1	MASTER EVENT # 2		
--------	------.0	45.20	75.75	14	4.1	EPB		
19831016	030046.7	45.61	75.06	12	3.1	111.7	4.0	3.0
--------	---------	45.62	75.05	12	3.1	EPB		
19831210	074357.8	45.75	74.66	18	2.8	25.1	10.0	6.0
--------	-----	45.70	74.77	11	2.8	EPB		
19831228	122423.7	47.04	76.24	17	3.5	107.5	5.8	4.0
--------	-----2.0	47.07	76.28	18	3.5	EPB		
19850824	060405.9	45.49	76.68	15	3.1	12.0	25.1	11.0
-------	-----	45.68	76.65	18	3.1	EPB		



0 50 100 150 200 km

1 : 2500000

Legend

M_b	
1.0	·
2.0	•
3.0	•
4.0	+

Figure 3.6. JHD locations with error bars (90% confidence limits) for selected events with stable solutions in the study area.

Lambert Conformal Projection Files: jhd.plt

3.3 Relocation of Local Earthquakes Using the "HYPOCENTER" Code

HYPOCENTER is a recent earthquake location method based on a least squares solution which combines features of the well-known and widely used algorithms "HYPO71"(Lee and Lahr, 1972) and "HYPOINVERSE" (Klein, 1978) with a new technique called adaptive damping (Lienert et al., 1986). This procedure adds a variable damping factor to the normal iterative process for minimizing the travel time residuals as a means of faster and demonstrably more accurate hypocentral determination. The scheme is such that if the root mean square of residuals (rms) increases in any iteration, the process returns to the previous solution increases the least square damping factor and tries again for a better convergence.

This procedure was used to test and calibrate the crustal velocity models and to carry out an analysis of mislocation errors as discussed in section 2 of the present report. Using the proposed velocity models for southern Ontario and western Quebec, a group of adequately recorded local events were also relocated using the HYPOCENTER code to test the advantages of this program and to compare with the JHD runs for the local events. Some modifications to the code and re-formatting were necessary to utilize this program for processing the GD/GSC data file of 1978-1987 which is available on computer tape.

A summary of the results are given in Table 3.4. An example of the full output of the iterative process are attached as Appendix I. A plotting routine, "PLOTEPI", has also been developed in this study for quick inspection of the relocated events. Copies of the plotted epicenters can be retrieved by screen dump as presented in Figures 3.6 and 3.7. A new code (HYPOFORM) developed for this study to sort the GD/GSC computerized data file on the basis of the quality A and B phase entries recorded by different combination of stations. This practice is thought necessary to avoid the errors due to station biasing and to the variable quality of the input data. HYPOFORM also converts both the input data to a format readable by the HYPOCENTER program and the output file to an appropriate format for plotting routines.

The resulting relocated earthquakes (Table 3.4 show small travel time residuals (average rms of less than .4 sec) and average calculated horizontal error limits of less than 2km. The magnitude estimates are based on duration (or coda length) of the signal with constant parameters developed for western United States and therefore, may not be as reliable as the amplitude magnitudes reported by GS/GSC. Eastern Canadian magnitue-coda parameters remain to be developed from futher analysis of available data in the next task.

Table 3.4: Relocated local hypocenters using the HYPOCENTER code.

DATE	ORIGIN	LAT N	LONG W	DEPTH	MAG	NO	GAP	DMIN	RMS	ERH	ERZ
810318	13 3 24.72	45- 2.78	74-58.21	.04	3.18	7	266	117.5	.12	.6	1.4
810319	1613 12.80	45-49.90	74-56.16	1.34	2.20	7	167	111.5	.26	2.1	99.9
810614	2334 46.91	45-47.35	74-59.50	9.78	2.75	6	171	71.7	.17	1.6	1.8
810625	955 16.59	45-33.11	74-25.11	14.25	3.39	10	188	63.7	.33	1.7	2.3
810721	17 0 15.18	45-32.35	74-25.34	.01	2.86	6	190	246.7	.23	.9	1.8
810727	924 4.17	46-43.19	75-34.10	9.16	2.94	9	112	113.2	.40	2.9	2.4
810731	337 23.57	45-51.74	74-34.59	23.63	2.88	9	157	73.4	.21	1.3	1.8
810916	735 29.52	45-57.85	74-47.17	1.13	3.10	8	153	61.5	.15	.0	9.8
810918	716 8.31	46- 3.62	75- 2.73	15.46	2.54	9	150	51.9	.40	2.4	2.8
810920	2217 45.94	45-48.64	74-21.33	21.47	3.24	9	156	68.4	.24	1.5	2.2
810925	1942 52.25	46-10.86	75-31.24	19.60	3.40	8	147	170.2	.29	.8	.7
810930	2341 39.58	46-21.45	75-36.40	1.20	2.69	9	135	73.5	.45	.1	33.2
811112	1840 14.27	47- .03	76-57.81	.14	2.97	10	216	261.1	.78	1.9	4.9
811115	1948 17.77	46- 3.31	75- 2.98	10.00	2.79	4	150	130.3	.07	.5	2.9
811220	2 5 10.06	45-42.00	74-46.37	5.22	3.11	8	176	56.1	.07	.4	.8
820206	1325 53.30	46-22.09	74-28.58	12.21	3.45	10	117	107.1	.44	2.1	2.0
820623	021 46.82	48-13.96	77-28.08	.00	4.86	5	45	432.5	.07	3.4	2.4
820806	629 10.34	45-54.17	75-25.02	18.40	4.19	7	167	22.6	.21	1.6	1.4
820813	1 6 37.84	46-33.77	78-53.32	.04	4.06	10	99	130.3	1.25	10.9	11.5
821031	2047 26.37	45-34.44	74-27.65	11.85	4.45	9	186	67.4	.29	1.3	3.6
821107	1826 5.98	46-18.44	75-15.42	17.36	4.13	5	135	159.4	.05	1.2	1.9
821107	1826 32.92	46-21.70	75-10.58	17.65	4.73	7	131	151.1	.69	2.8	3.8
821124	734 41.26	45-23.05	73-30.43	10.50	3.94	5	70	322.0	.11	1.6	.7
830305	744 8.32	46- 8.70	74-42.46	13.37	4.40	9	138	113.4	.23	1.4	1.2
830717	2247 45.52	46- 3.84	74-56.27	24.58	4.45	10	148	58.0	.29	1.9	2.0
830717	2312 7.36	46- 6.16	74-56.23	18.17	4.16	9	145	125.4	.26	1.9	2.2
830718	5 6 51.67	45-50.73	74-52.36	8.73	3.90	8	165	50.3	.16	.9	1.3
831004	1718 41.94	43-13.82	79-53.70	.59	4.54	10	76	49.7	5.03	36.0	30.1
831011	410 55.29	45-12.24	75-45.78	16.17	4.16	7	295	21.4	.15	1.0	.8
831016	3 0 47.28	45-37.14	75- 3.71	20.12	4.58	9	190	34.6	.23	1.1	2.2
831030	1214 11.68	43-56.90	74-20.70	4.67	4.29	7	317	196.6	.38	4.1	2.1
831101	1016 51.71	45-43.81	73-51.19	20.65	4.04	9	134	31.7	.19	1.4	1.1
831123	222 4.72	44- 1.96	74-20.14	20.54	3.95	5	316	132.7	.33	5.7	4.2
831210	743 54.77	45-43.91	74-45.97	16.38	3.88	9	173	56.6	.16	.8	1.2
831221	15 4 44.66	45-13.64	73-58.01	13.24	3.49	9	254	141.2	.19	1.3	1.2
840117	19 4 46.48	45-34.42	75- 8.07	23.17	1.98	9	205	31.2	.17	.7	1.1
840303	922 24.82	46-20.00	74-50.94	19.61	4.24	8	128	135.9	.38	.9	1.2
840628	3 8 49.68	46-14.27	75-40.90	15.81	4.24	9	144	184.5	.21	1.5	1.4
840820	1058 16.37	44-54.71	73-28.08	11.35	3.91	10	74	67.1	.44	3.1	1.9
841126	9 3 49.16	45-10.69	75- 4.52	20.38	3.49	8	259	25.1	.13	.7	.9
850130	946 13.26	45-46.16	75- 8.70	13.65	3.65	6	175	125.4	.17	1.2	5.8
850206	2311 47.21	46-29.30	73-53.37	4.03	4.45	6	92	186.7	.37	3.9	4.5
850410	918 39.94	45-35.41	74-55.91	10.12	3.45	7	192	45.5	.10	.5	.8
850516	1339 6.92	46-51.48	75-56.27	2.10	4.12	9	103	240.0	.19	1.4	1.1
850824	6 4 2.22	45-37.84	76-40.60	1.16	3.03	9	219	73.9	.37	2.9	5.1
851110	1421 28.07	46-29.92	75-48.85	1.07	1.78	7	125	208.3	.41	.1	99.9
860507	1729 56.70	45-52.82	75-22.19	22.90	1.82	7	169	146.1	.34	1.3	.9
860515	050 18.55	45-32.09	74-31.45	6.47	1.15	7	192	238.8	.03	.2	3.0
860605	1213 22.01	46-21.49	75- 1.13	19.55	3.50	9	130	80.6	.64	.8	1.4
860618	412 2.07	45-55.60	74-46.79	11.89	3.09	9	157	104.5	.47	3.1	3.3
860720	1315 13.38	45-34.27	74-13.43	14.86	2.70	10	182	48.6	.20	1.4	1.4
860802	837 30.99	45-40.61	73- 7.38	10.00	2.61	6	32	43.7	.72	19.5	7.9
860802	956 3.53	45-28.91	74-31.98	.18	1.74	7	200	94.6	.37	.8	2.6
860806	1119 36.43	46-24.51	75-13.64	22.10	4.59	7	129	80.3	.22	2.2	1.4
870205	1921 1.15	46-41.69	77-16.66	.11	2.57	10	174	320.8	1.38	5.4	10.9
870420	343 39.24	45-33.69	74-46.39	21.64	1.87	10	192	58.6	.52	2.3	2.6

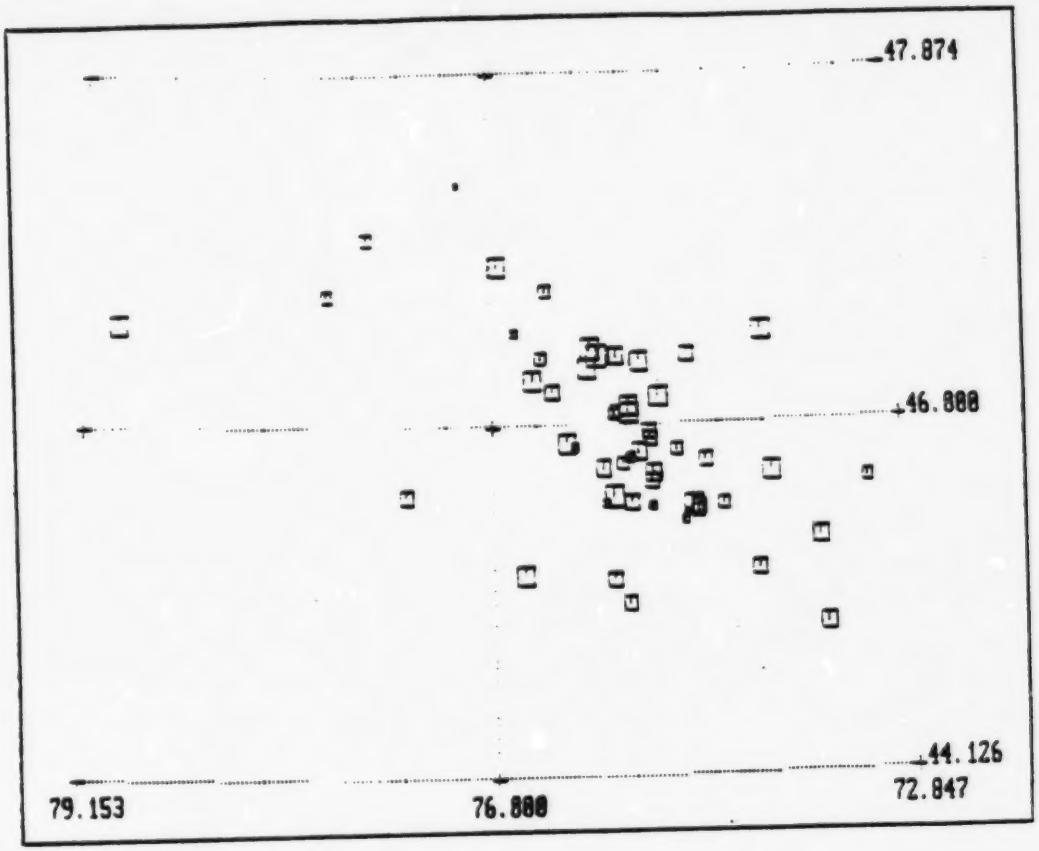


Figure 3.7:

A plot of small magnitude well-recorded events in western Quebec (1981-1987), recomputed by the HYPOCENTER code.

4 SEISMICITY PATTERNS AND DELINEATION OF ACTIVE TRENDS

It is generally accepted that earthquakes primarily occur on or close to pre-existing faults in the earth's crust. These faults are generally identified on the basis of the following criteria:

1) Surface expression of the active faults which can be mapped at ground surface.

2) Fault plane solutions of the earthquakes, determined through polarity distribution of the first phase arrivals on the focal sphere.

3) Inferred fault planes through visual identification or statistical analysis of the distribution of hypocenters.

Surface mapping of an active fault is reliable if it is possible to find a trace at the ground surface and to establish the geological history of movements. However, surface mapping cannot identify changes in fault orientation with depth nor can the location of subsurface fractures parallel or subparallel to mapped traces of faults be identified.

Fault plane solutions do give an indication of the fault orientation where it is possible to determine, but there is ambiguity in determining which of the nodal planes is actually the causative fault plane.

Epicentral locations of earthquakes, if related to vertical or near vertical fault planes, should normally define linear features which are known as seismic trends. But in most cases, such as southern Ontario and western Quebec, identification of specific seismic trends has been difficult because the event locations may be of insufficient accuracy or because earthquakes may occur at erratic locations along low dipping fault planes or along nonparallel randomly distributed faults.

Having reviewed the range of inaccuracies in earthquake locations in the study region and with re-computation of a group of hypocenters, an attempt to re-interpret the existing data with the aim of identifying the most prominent seismic trends has been made. Visually determined linear seismic trends at NW and NE directions, are presented in this study. These seismic trends have been screened in several steps and are categorized on the basis of the confidence weighting system adopted in the following paragraphs.

4.1 Methodology to Specify Seismic Trends

Three definitions have been adopted in order to differentiate between variations in the likelihood of association of epicenters with certain preferred trends. The following classifications are used to describe the more prominent seismic trends relative to others which may be apparent.

- Seismic trend A; defined by alignment of five earthquakes of Mb>4.

- Seismic trend B; defined by alignment of four earthquakes of Mb>4

- Seismic Trend C; defined by alignment of any combinations of three earthquakes of M_L>3

It is generally believed that microearthquakes (M_L< 3) may not be associated with fault rupturings of significant lengths. On the basis of the latest empirical relations given by Darragh and Bolt (1987) for earthquakes of magnitude smaller than 4, subsurface faulting may not exceed 1 to 2 km (Figure 4.1). Therefore, caution should be exercised in connecting them to the same source when the hypocentral relations between them exceed much longer distances.

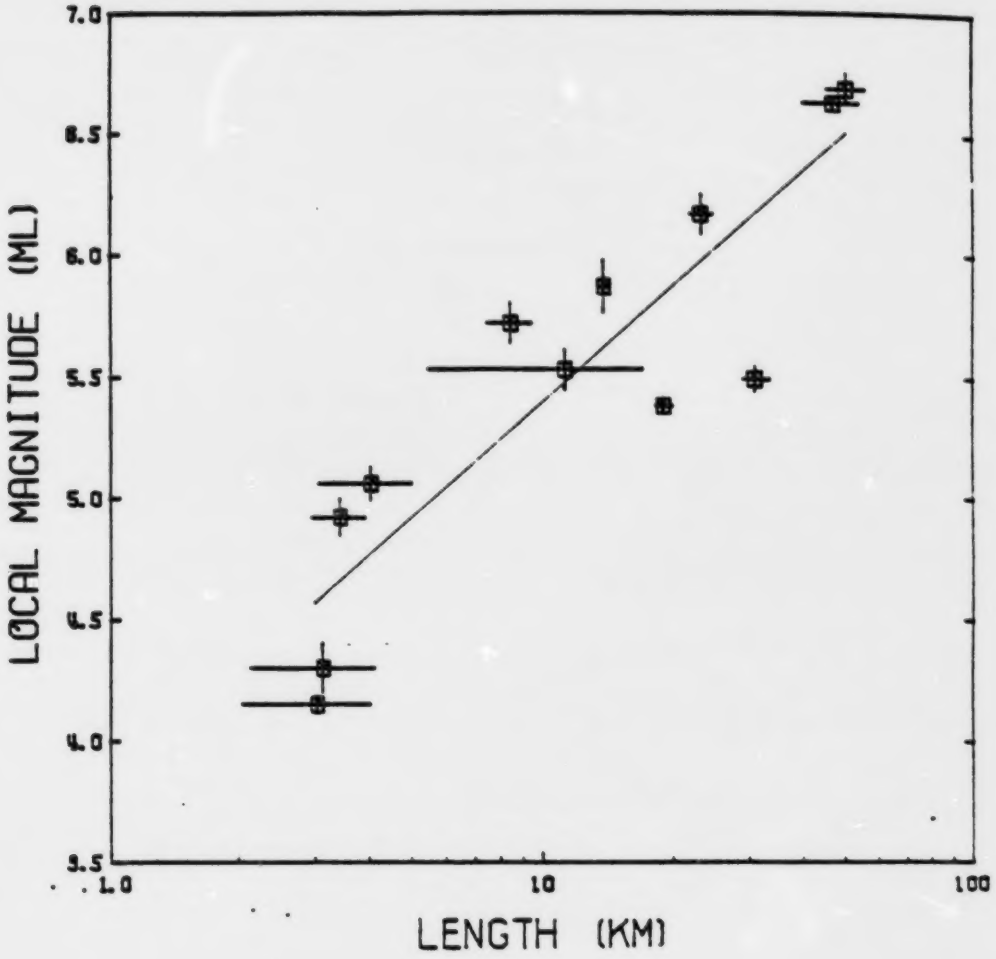


FIGURE 4.1: Relation between local magnitude (M_L) and length of aftershock zone as a measure of the subsurface fault rupture. A line in the form of $(M_L) = 3.82 \pm 0.289 + (1.58 \pm 0.52)$ Log L fits the data (after Darragh and Bolt, 1987)

Nevertheless, it is proposed that detailed statistical analyses of all the possible inferred faults and fracture systems be carried out as a continuation of the present study into the next task. The basic assumption in this technique is that many earthquakes fall along one or more parallel planes in the Earth's crust. In order to define the trend of a fault plane, more than three earthquakes must fall along it . The more earthquakes that fall along a given plane, the better determined will be the location and hence the orientation of the trend.

The principal on which this method is based considers the unique combinations of three earthquakes (N_c) in a set of N earthquakes that have occurred along one plane, which is limited as a rule to:

$$N_c = N(N-1)(N-2)/6$$

Lutz (1986), Michelini and Bolt (1986) and Fehler et al (1987) used same principal but with different approaches to: a) identify lineaments in two-dimensional geological data, b) a study of aftershocks of 1983 Coalinga, California earthquake, and c) study faulting and fracturing associated with hydraulic fracturing, respectively.

4.2 Seismic Trends

A preliminary attempt has been made to classify certain linear seismicity patterns which have been recognized in the study region. This practice is based on the assumption that moderate to large magnitude earthquakes may be generated on relatively larger fault planes or linear structurally weak zones. The most prominent trend seems to extend in a 130°-310° directions with more than five associated earthquakes of M>4. Two trends of similar strike (azimuth of about 130°) are identified passing at 80 and 130 km to the north of Ottawa. A conjugate set striking at 040° is also inferred which crosses the previous trends in several places (Figure 4.2). Lack of detailed geological information in western Quebec doesn't permit one to one cross correlation of these seismic trends with a mapped surface structure. However, compilation of all the latest available geological structures, including the lineament on satellite imagery mapped by Sanford et al (1985), as presented in Figure, 4.3 show similar general northwest and southeast structural trends. A recent study of the statistical fracture orientations of the Canadian shield by Lowman (in press), as demonstrated in Figure 4.4, also shows

dominant trends at 040, 070 and 315 which are compatible with the inferred direction of the seismic trends suggested in this study. These trends are also in general agreement with dominant strikes of the nodal planes (Figure 4.5) of the recent fault plane solutions published for this region (Wahlstrom, 1987).

The seismic trends are also compared with deduced linear structures on a magnetic anomaly map prepared with the multi-directional sun shadow technique to enhance the linear magnetic features (Figure 4.6 courtesy of Urquhart-Dvorak Ltd and Lamontagne Geophysics Ltd). Most of the magnetic lineations on this image are diabasic dikes, representing former weak planes in the crust into which the intrusive bodies were emplaced. A cluster of relocated earthquakes in the Timiscaming area falls near the mapped dikes of the Ottawa-Bonnechere graben which trend at a general WNW direction. Armbruster and Seeber (1987) also introduced an almost N-S trending dike in Lancaster county, Pennsylvania as the source of local seismicity. In addition to the WNW and E-W striking dikes, other linear trends, mainly to the NW and NE are also recognized on the magnetic anomaly map. These observations may indicate the existence of certain preferred structural trends in western Quebec and southern Ontario.

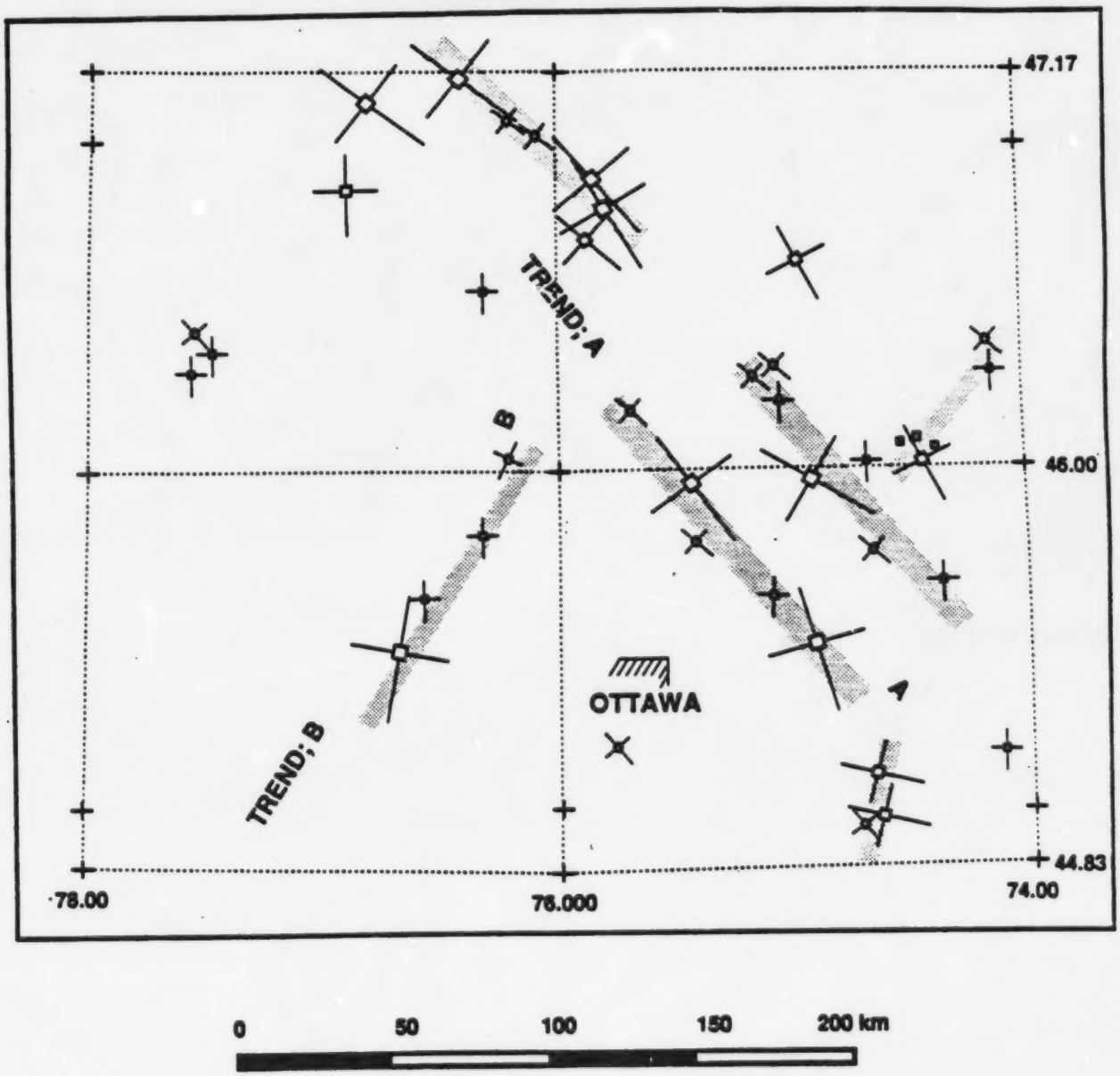
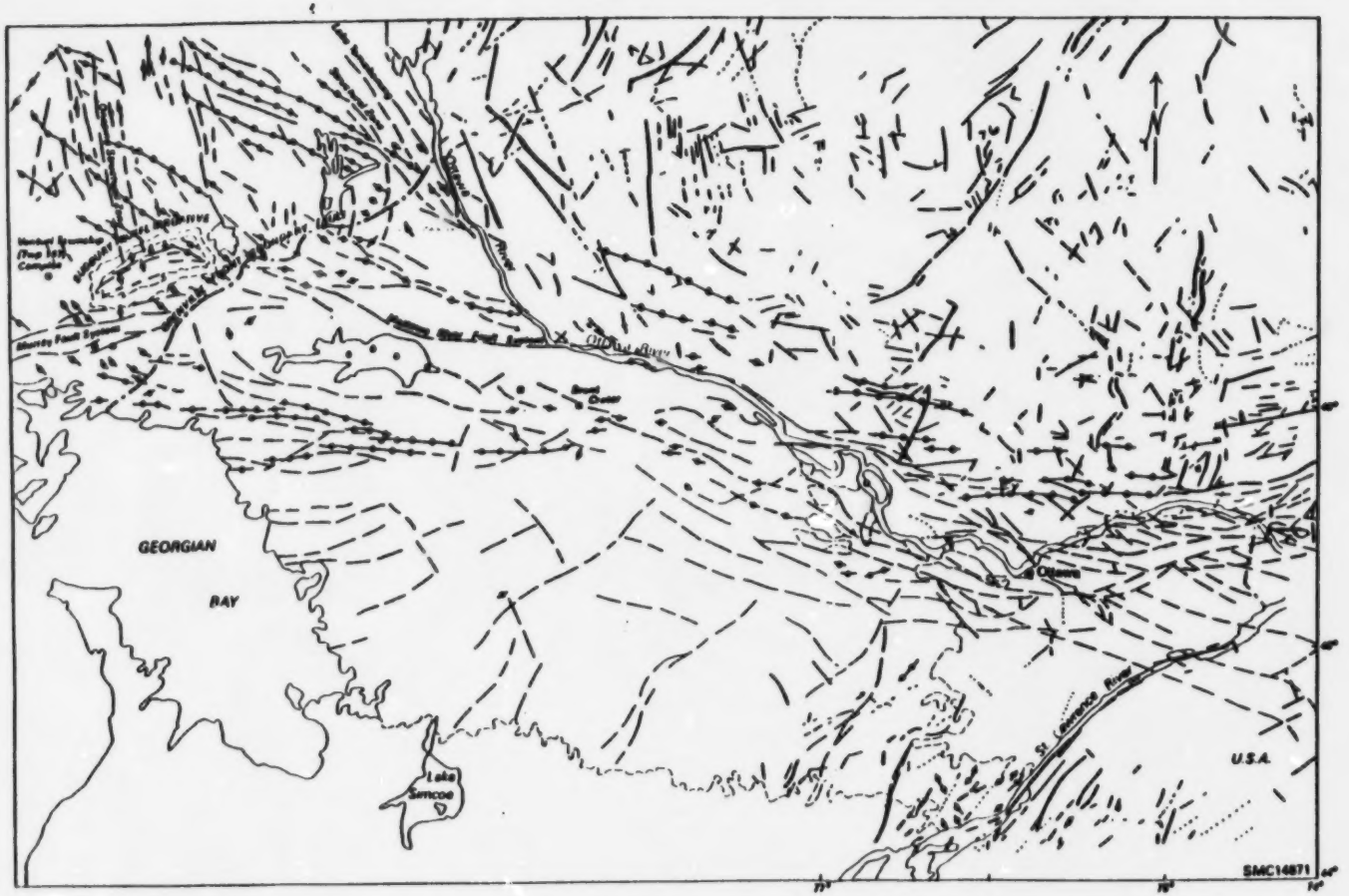


FIGURE 4.2: Joint Epicenter Determination (JED) of selected earthquakes in the West Quebec Seismic Zone (WQSZ). Error bars show 90% confidence limits of the recomputed locations.



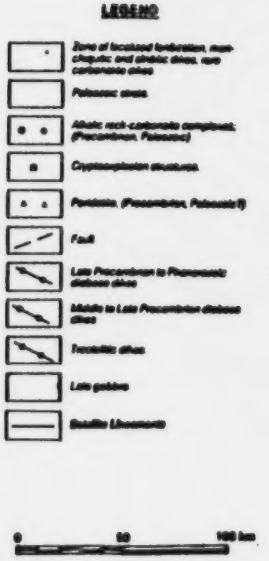


FIGURE 4.3: Geologically mapped faults (blue lines), faults inferred from geological and geophysical data (after Forsyth, 1981; Lumbers 1982) and the Satellite Lineaments (black lines; after Sanford et al., 1985)

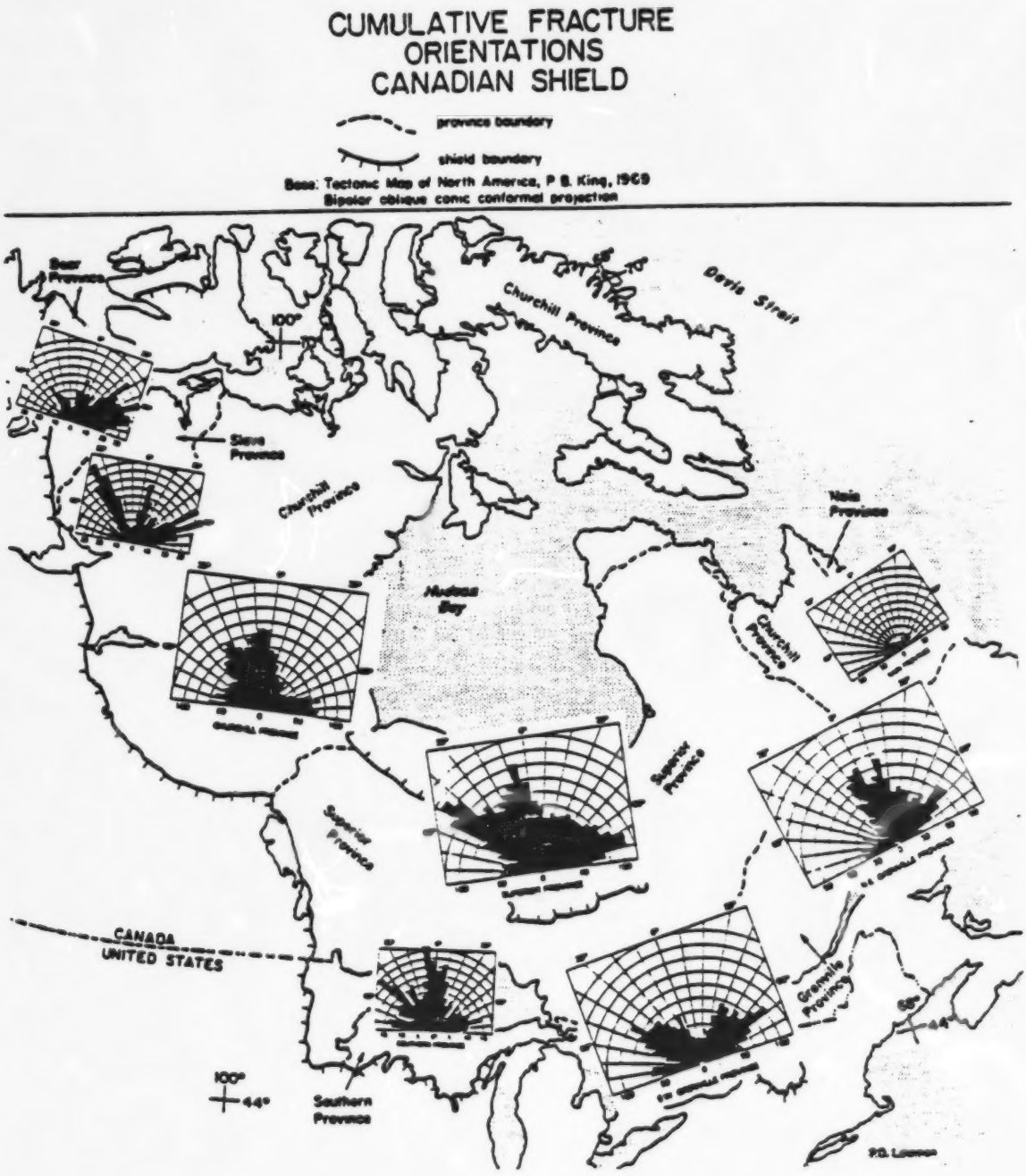


Figure 4.4: Fracture patterns of the Canadian shield (after Lowman et al., in press).

4.3 Causative Mechanism of the Seismicity in the Study Region

The approach adopted to explain the causative mechanism of seismicity in the study region basically relies on the Mohr-Coulomb failure criterion (Jagger and Cook 1971) which provides a simple representation of the failure process in rocks (Figure 4.7). Influences of pre-existing weak zones and/or induced stresses can also be incorporated into the theoretical analyses of earthquake distributions and their associated rupture planes whether or not they are known or mapped at the ground surface.

Since the inherent shear strength of intact rock is considerably larger than that for pre-existing failure surfaces, failure in previously fractured rock may occur first on pre-existing planes other than at the angle and as defined by the Mohr diagram for failure criterion.

In addition if the rock is subjected to internal fluid pressure P, the compressive stresses will be opposed by the hydrostatic fluid pressure, and the effective principal stress components will be reduced to 6i-P (Simpson 1976) and therefore the failure criterion becomes,

$$\tau = \tau_o + \mu (G_n - P)$$

where:

- τ is shear stress
- τ_o is the rock cohesion
- μ is the coefficient of friction
- G_n is normal elastic stress
- P is pore pressure

This effect can be presented on the Mohr circle by translation of the circle to the left by an amount equal to the magnitude of the fluid pressure.

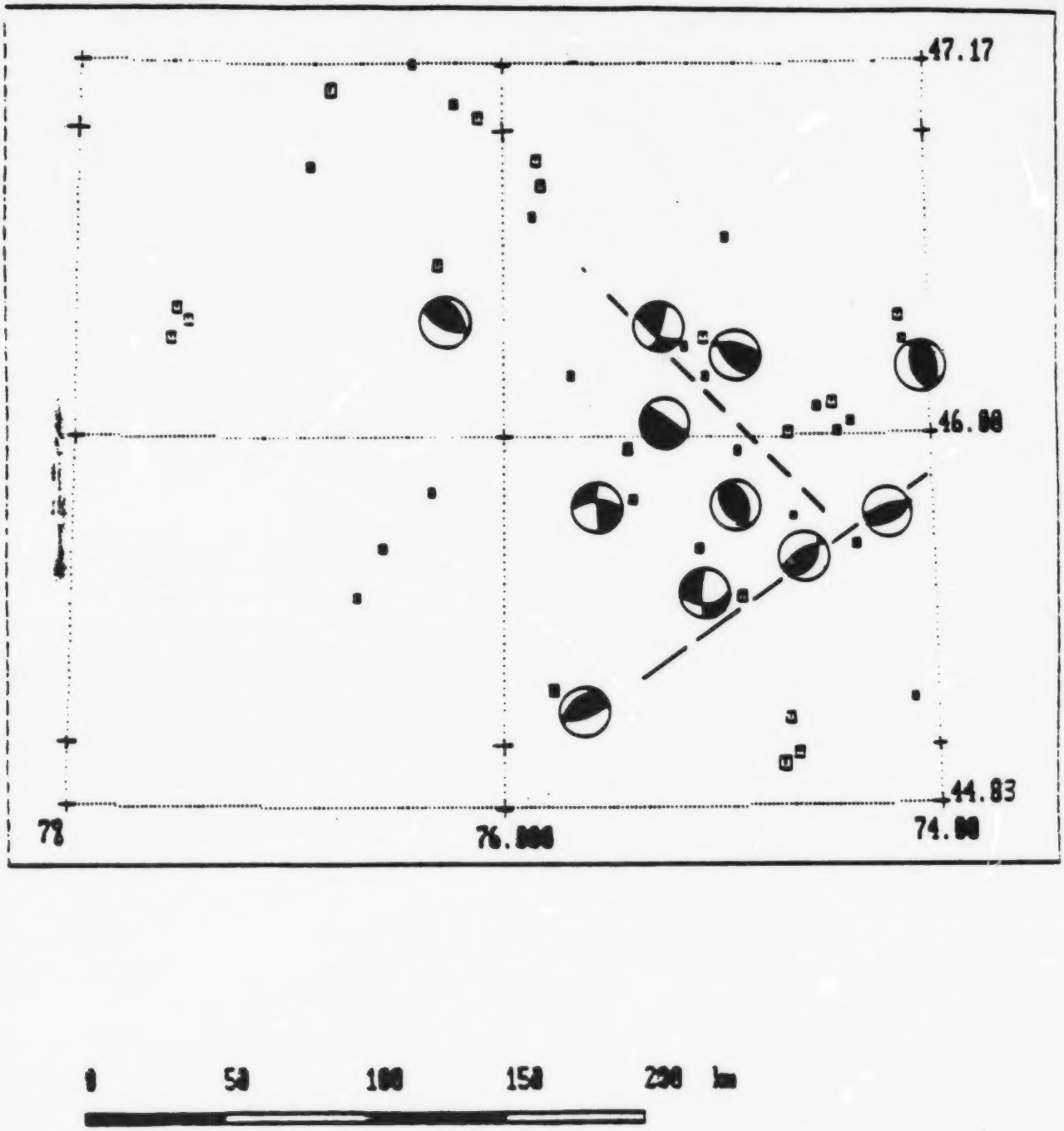
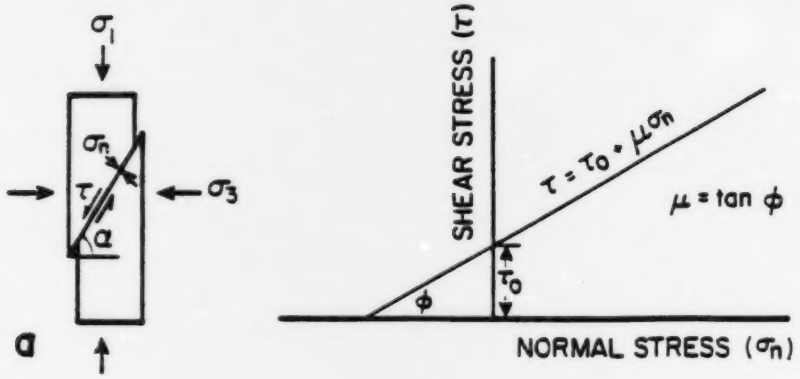
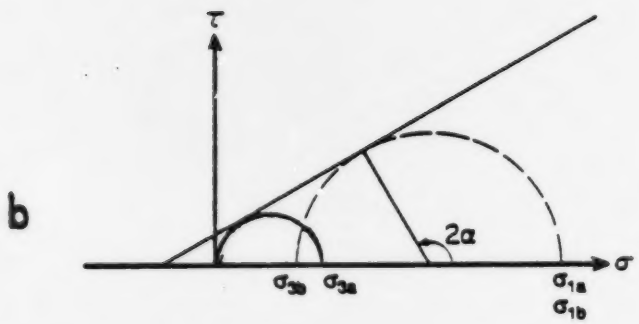


Figure 4.5: Two dominant directions of the nodal planes, based on the available fault plane solutions in the study region (Wahlstrom, 1987), extending NW and NE, which are in general accord with the inferred seismic trends.



Coulomb's Law for failure in dry rock

τ = shear stress σ_n = normal stress
τ = cohesion $\mu_{(\tan\phi)}$ = coefficient of friction



The Mohr-Coulomb failure criterion

FIGURE 4.7: A graphical presentation of the role of triggering mechanism in reducing the principal stress (σ_3) or both σ_1 and σ_3 to create a failure condition.

Thus, in a highly fractured, Precambrian crust such as is found in southern Ontario and western Quebec, as demonstrated by Sanford et al., (1985), it is reasonable to assume that under the prevailing high compressive stresses existing faults and fractures or weak planes may undergo differential movements, generating earthquakes of varying magnitude and depth. Of course, the near-surface fractures and faults with associated smaller shocks may be more controlled by such effective induced stresses as groundwater fluctuations, planetary gravitational forces and deglaciation rebound. The moderate to larger magnitude earthquakes would then be related to more prominent and deep seated structures which can accommodate considerable strain build-up before a seismogenic slippage.

5 CONCLUSIONS AND RECOMMENDATIONS

The apparent diffused pattern of earthquake distribution in southern Ontario and western Quebec is effected by mislocation errors. The dominant sources of error are systematic biasing of seismographic stations used to compute the hypocenters, in different periods and regions, in addition to the quality of the recorded signals and data reduction techniques. Accuracies of better than +/- 2km in locating the earthquakes are possible within the ECTN with special treatment of the weighting factors of the phase onset readings. Locations given for earthquakes prior to 1974 and for the events generated in southern Ontario may be within +/- 20km of the actual location, and could be more for microearthquakes (M<3).

A preliminary interpretation of seismicity pattern evident from the relocated earthquakes reveals several alignments of epicenters along seismic trends extending to the northwest (NW) and to the northeast (NE) across the Ottawa River into western Quebec. the NW seismic trends are also observable with recent and more accurate locations published in the ECTN bulletins for magnitudes larger than 3. Delineated trends of the linear seismic sources coincides with identical azimuths of about 040° and 130° inferred from the statistical analysis of the fracture patterns as mapped on satellite imageries, suggested by linear magnetic anomaly features and nodal planes of some of the available fault plane solutions. Geological field investigations and seismic experiments along the indicated seismically active trends may provide further evidences to their causative mechanism.

Re-examination of the original seismograms is a feasible undertaking to improve the data base for site specific studies. Concurrently, a better instrumental coverage of the southern Ontario is required to substantially increase the location accuracy and to help in understanding the causative mechanisms, the potential for and constraints on generating a severe ground shaking in the future. The recommended deterministic approach is to identify and characterize the real seismic sources for site specific hazard evaluations. This approach is demonstrably capable of reducing the uncertainties associated with purely probabilistic seismic risk assessment, which usually depend on various theoretical assumptions or speculative models.

6 ACKNOWLEDGEMENTS

I am grateful to Professor Gordon West and Professor George Garland and other colleagues in the Department of Physics for their trust, scientific support and providing the access to all the facilities in University of Toronto. This work would have not been possible without the generous co-operation of the staff of Geophysics Division of the Geological Survey of Canada. Many thanks are due to Peter Basham for suggesting the study, Robert Wetmiller for providing the computer data file, John Adams for scientific discussions, Maurice Lamontagne and Michael Plouffe for assistance in retrieving the data.

Technical interest and financial support of both Ontario Hydro and the Atomic Energy Control Board of Canada were behind all the activities related to this project. I am specially indebted to Earle Taylor, Chack Lee, John Bowlby, Joseph Wallach, Harold Asmis and James Grass for their assistance and encouragement throughout the present study. In addition, I had the privilege of attending the Multi-Agency Group for Neotectonics of Eastern Canada (MAGNEC) meetings which provided a forum for stimulating technical discussions that were helpful for improving the results of this study. I extend my appreciation to John Bowlby for his follow up of the study progress and editorial review of the manuscript.

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8 APPENDIX - A

Examples of the HYPOCENTER Computations for Sensitivity Analysis

APPENDII A.Recomputed locations for COCRUST Explos. using HYPOCENTER code.

——— HYPOCENTER VERSION 1.2 8/19/86 ———

```
RESET TEST( 1)=  10.0000
RESET TEST( 2)= 500.0000
RESET TEST( 3)=    .5000
RESET TEST( 5)=   1.0000
RESET TEST( 6)=   1.0000
RESET TEST(11)=  20.0000
RESET TEST(13)=  10.0000
RESET TEST(30)=    .0050
RESET TEST(31)=   2.0000
RESET TEST(36)=    .0000
RESET TEST(37)=   6.0000
RESET TEST(33)=    .0000
RESET TEST(41)=1000.0000
RESET TEST(42)=    .0000

 DUMY4401.00N 7600.00W 100   .00  .00
 DAM 4400.00N 8000.00W 100   .00  .00
 SANY4310.43N 7852.22W 172   .00  .00
 CROS4354.30N 7524.75W 244   .00  .00
 DANY4450.14N 7345.43W 507   .00  .00
 DMN 4249.53N 7811.58W 491   .00  .00
 MED 4401.11N 7822.46W 149   .00  .00
 OTT 4523.65N 7543.00W  77   .00  .00
 MBO 4500.01N 7516.50W  85   .00  .00
 CXO 4559.66N 7727.00W 190   .00  .00
 MEDY4310.91N 7823.42W 186   .00  .00
 PNY 4450.05N 7333.30W 177   .00  .00
 LDO 4100.25N 7354.55W  91   .00  .00
 PAL 4100.25N 7354.55W  91   .00  .00
 PTN 4434.35N 7458.97W 238   .00  .00
 GAC 4542.20N 7528.70W  62   .00  .00
 GRQ 4636.40N 7551.60W 290   .00  .00
 TRQ 4613.33N 7433.34W 853   .00  .00
 EED 4638.46N 7904.38W 398   .00  .00
 ALX 4419.35N 7555.68W 121   .00  .00
 DNY 4250.18N 7810.13W 381   .00  .00
 CFO 4528.15N 7613.75W  70   .00  .00
 MIQ 4622.20N 7558.20W 199   .00  .00
 LN  4408.70N 7651.75W  93   .00  .00
 VDQ 4813.80N 7758.30W 305   .00  .00
 JAQ 5348.13N 7543.16W 366   .00  .00

 6.100   .000   .000
 6.400  1.000   .000
 6.600 16.500   .000
 6.800 26.000   .000
 7.000 32.000   .000
 8.000 38.000   .000
 8.200 46.000   .000
```

```
 0.          1.75

***** DEPTH FIXED BY OPERATOR .. IRES = 1 OR TEST(31)=2 *****


  FIRST ARRIVAL =   820805 10 25 12.32


ITER   ORIGIN   LAT N   LONG W DEPTH NO  M    RMS   DAMP.   ERLG  ERLT  ERDP
        (SEC)  (DG MN) (DG MN)  (KM)          (SEC)          (KM)  (KM)  (KM)
  1    -1.30 4401.19 7822.35   .10  7  2 12.116   .005    .0    .0    .0
  2      .47 4427.46 7734.81   .10  7  2   .783   .005   75.4  77.4 558.2
  3      .40 4428.07 7738.71   .10  7  2   .503   .005    3.7   4.7  36.8
  4      .39 4428.14 7738.85   .10  7  2   .503   .005    2.4   2.9  15.3

  DATE      ORIGIN   LAT N   LONG W DEPTH NO  M   RMS DAMP. ERLN ERLT ERDP ICD
820805 10 25   .39 4428.14 7738.85   .10  7  3  .503 .005  2.5  3.7 10.5   3

DRMS VALUES: D=   10.00 KM

DRMS:       LON+0     LON-0     LAT+0     LAT-0   DEPTH+0   DEPTH-0
 DRMS NEG     .91       .86       .71       .65       .24       .00

RESOLUTION MATRIX:          LONG     LAT   DEPTH
                   LONG     .985    .014   -.003
                   LAT      .014    .977    .010
                  DEPTH    -.003    .010    .990

  STN  DIST AZM AIN PRMK HRMN P-SEC TPOBS TPCAL DLY/HI P-RES P-WT AMX PRX CALX K XMAG RMK FMP FMAG S
RMK S-SEC TSOBS S-RES  S-WT
 WED   77.1 230  72  P 0 1025 12.32 11.93 12.14   .00  -.21  1.22                              4.2
S 1 21.93 21.54   .29   .91
 WBO  197.9  72  72  P 2 1025 30.78 30.39 31.02   .00  -.63   .61                              .0
S 2 56.23 55.84  1.55   .61
 GAC  220.3  51  49  P 0 1025 34.16 33.77 34.03   .00  -.26  1.22                              4.7
  4
 TRQ  312.7  51  48  P 0 1025 45.30 44.91 45.40   .00  -.49  1.22                              .0
  4
 VDQ  417.8 338  48  P 0 1025 58.90 58.51 58.21   .00   .29  1.22                              .0
  4

UNWEIGHTED RMS =    .69

***** DEPTH FIXED BY OPERATOR .. IRES = 1 OR TEST(31)=2 *****


  FIRST ARRIVAL =   820807 10 25 12.39


ITER   ORIGIN   LAT N   LONG W DEPTH NO  M    RMS   DAMP.   ERLG  ERLT  ERDP
        (SEC)  (DG MN) (DG MN)  (KM)          (SEC)          (KM)  (KM)  (KM)
  1    -1.83 4401.19 7822.35   .10  7  2 11.390   .005    .0    .0    .0
```

```
   2     .79 4425.64  7733.09   .10  7  2   .923    .005  74.4  78.4 651.8
   3     .63 4425.80  7737.63   .10  7  2   .485    .005   4.5   6.3  47.6
   4     .63 4425.97  7737.84   .10  7  2   .484    .005   2.4   3.2  13.1

  DATE      ORIGIN    LAT N   LONG W DEPTH NO  M    RMS DAMP. ERLN ERLT ERDP ICD
 820807 10 25   .63  4425.97  7737.84   .1* 7  3   .485 .005  3.0  4.2  8.6   3

 DRMS VALUES: D=   10.00 KM

 DRMS:       LON+D     LON-D     LAT+D     LAT-D   DEPTH+D   DEPTH-D
  DRMS MEA     .93       .88       .65       .59       .15       .00

 RESOLUTION MATRIX:          LONG      LAT    DEPTH
                    LONG     .975     .024    -.010
                    LAT      .024     .972     .011
                   DEPTH    -.010     .011     .991

  STN  DIST AZM AIN PRMK HRMN P-SEC TPOBS TPCAL DLY/HI P-RES P-WT AMX PRX CALX K XMAG RMK FMP FMAG S
RMK S-SEC TSOBS S-RES  S-WT
 MEO   75.6 233  72  P 0 1025 12.39 11.76 11.90   .00  -.14 1.12                                .0
S 1 21.72 21.09  .26   .84
 OTT  186.1  55  72  P 0 1025 29.63 29.00 29.17   .00  -.17 1.12                                .0
S 2 33.15 32.52 1.47   .56
 WBO  197.9  71  72  P 0 1025 31.00 30.37 31.02   .00  -.65 1.12                                .0
  4
 TRO  314.2  50  48  P 0 1025 46.59 45.96 45.58   .00   .38 1.12                                .0
  4
 VOO  421.9 338  48  P 0 1025 59.00 58.37 58.71   .00  -.34 1.12                                .0
  4

 UNWEIGHTED RMS =    .63

 ***** DEPTH FIXED BY OPERATOR .. IRES = 1 OR TEST(31)=2 *****


  FIRST ARRIVAL =  820811 10 25 12.46


 ITER   ORIGIN   LAT N   LONG W DEPTH NO  M    RMS    DAMP.   ERLG  ERLT  ERDP
        (SEC)  (DG MN)  (DG MN)  (KM)          (SEC)           (KM)  (KM)  (KM)
   1    1.40 4401.19  7822.33   .10  6  2 13.276    .005     .0    .0    .0
   2     .34 4424.15  7729.18   .10  6  2  1.220    .005  110.5 113.4 854.9
   3     .42 4423.75  7733.78   .10  6  2   .733    .005    7.6  10.9 111.0
   4     .43 4424.00  7734.05   .10  6  2   .733    .005    4.6   6.4  40.0
   5     .43 4424.04  7734.09   .10  6  2   .733    .005    4.6   6.3  40.0

  DATE      ORIGIN    LAT N   LONG W DEPTH NO  M    RMS DAMP. ERLN ERLT ERDP ICD
 820811 10 25   .43  4424.04  7734.09   .1* 6  3   .733 .005  5.5  7.8 14.2   3

 DRMS VALUES: D=   10.00 KM

 DRMS:       LON+D     LON-D     LAT+D     LAT-D   DEPTH+D   DEPTH-D
```

```
 DRMS NEG     .91       .98       .59       .52      -.02       .00

RESOLUTION MATRIX:          LONG     LAT   DEPTH
                    LONG    .961    .038   -.010
                     LAT    .038    .958    .011
                   DEPTH   -.010    .011    .992

  STN  DIST AZM AIN PRMK HRMN P-SEC TPOBS TPCAL DLY/HI P-RES P-WT AMX PRX CALX K IMAG RMK FMP FMAG S
PMK S-SEC TSOBS S-RES  S-WT
 MED   77.6 237  72  P 0 1025 12.46 12.03 12.21   .00  -.18 1.14                          .0
S 0 21.98 21.55   .18 1.14
 OTT  184.2  53  72  P 1 1025 31.06 30.63 28.87   .00  1.76  .86                          .0
  4
 MBO  194.4  69  72  P 1 1025 30.00 29.57 30.47   .00  -.90  .86                          .0
  4
 SAC  220.3  49  49  P 0 1025 34.12 33.69 34.04   .00  -.35 1.14                          .0
  4
 VDD  425.7 357  48  P 1 1025 59.22 58.79 59.18   .00  -.39  .86                          .0
  4

 UNWEIGHTED RMS =    .84

 ***** DEPTH FIXED BY OPERATOR .. IRES = 1 OR TEST(31)=2 *****


  FIRST ARRIVAL =  820805 11 35  8.31


 ITER   ORIGIN   LAT N   LONG W DEPTH NO  N    RMS   DAMP.   ERLS ERLT  ERDP
        (SEC)   (DG MN) (DG MN) (KM)              (SEC)          (KM) (KM)  (KM)
   1     8.48 4523.73  7542.89   .10  7  2 4.380   .005     .0   .0    .0
   2     6.53 4535.75  7548.14   .10  7  2 2.644   .005    12.9 12.0 144.7
   3     3.15 4535.29  7609.41   .10  7  2 1.220   .005    12.6  6.4 869.5
   4     2.80 4531.21  7612.06   .10  7  2  .877   .005     5.6  4.2 150.5
   5     2.78 4530.74  7612.24   .10  7  2  .872   .005     3.9  3.3  75.6
   6     2.77 4530.71  7612.27   .10  7  2  .872   .005     3.9  3.3  74.8

  DATE      ORIGIN   LAT N   LONG W DEPTH NO  N   RMS DAMP. ERLN ERLT ERDP ICD
 820805 11 35  2.77 4530.71  7612.27   .10  7  3  .872 .005  3.9  3.4 15.0   3

 DRMS VALUES: D=  10.00 KM

 DRMS:      LON+D     LON-D     LAT+D     LAT-D   DEPTH+D   DEPTH-D
  DRMS NEG    .38       .39       .53       .45       .20       .00

 RESOLUTION MATRIX:          LONG     LAT   DEPTH
                    LONG    .994   -.002    .000
                     LAT   -.002    .994    .001
                   DEPTH    .000    .001    .995

  STN  DIST AZM AIN PRMK HRMN P-SEC TPOBS TPCAL DLY/HI P-RES P-WT AMX PRX CALX K IMAG RMK FMP FMAG S
RMK S-SEC TSOBS S-RES  S-WT
```

```
OTT   40.7 108  72  P 0 1135  8.31  5.54  6.46   .00  -.92 1.27                          4.5
S 1 15.36 12.59  1.28  .95
WBO   93.1 127  72  P 1 1135 17.09 14.32 14.63   .00  -.32  .95                          .0
S 1 28.62 25.85  .24  .95
TRQ  151.7  58  72  P 1 1135 25.37 22.60 23.80   .00 -1.20  .95                          .0
S 1 44.62 41.85  .20  .95
VDQ  330.8 336  48  P 1 1135 31.40 48.63 47.60   .00  1.02  .95                          .0
 A

UNWEIGHTED RMS =   .86

***** DEPTH FIXED BY OPERATOR .. IRES = 1 OR TEST(31)=2 *****


  FIRST ARRIVAL =  820807 10 15  8.37


ITER   ORIGIN   LAT N   LONG W DEPTH NO  M    RMS    DAMP.   ERLG  ERLT  ERDP
       (SEC)  (DG MN)  (DG MN)  (KM)              (SEC)          (KM)  (KM)  (KM)
   1    5.63 4523.73  7542.89   .10  6  2 7.000    .005    .0    .0    .0
   2    3.01 4548.80  7548.42   .10  6  2 2.795    .005   26.0  21.3 395.2
   3    1.11 4542.10  7613.81   .10  6  2 1.447    .005   17.1   7.2 833.8
   4     .08 4533.19  7621.87   .10  6  2  .390    .005   10.9   8.1 230.6
   5    -.13 4530.60  7622.81   .10  6  2  .108    .005    2.9   3.1  18.4
   6    -.15 4530.39  7622.91   .10  6  2  .104    .005    .8    .9   1.4

  DATE      ORIGIN    LAT N   LONG W DEPTH NO  M    RMS DAMP. ERLN ERLT ERDP ICD
820807 10 14 59.85  4530.39  7622.91   .10  6  3   .108  .005   .8   .9  2.0   3

DRMS VALUES: D=   10.00 KM

DRMS:       LON+0     LON-0     LAT+0     LAT-0   DEPTH+0   DEPTH-0
  DRMS NES   1.02      1.03       .90       .76       .45       .00

RESOLUTION MATRIX:          LONG      LAT    DEPTH
                   LONG     .974    -.020    -.006
                    LAT    -.020     .979    -.003
                  DEPTH    -.006    -.003     .993

 STN  DIST AZM AIN PRMK HRMN P-SEC TPOBS TPCAL DLY/HI P-RES P-WT AMX PRX CALX K XMAG RMK FMP FMAG S
RMK S-SEC TSOBS S-RES  S-WT
OTT   54.1 103  72  P 0 1015  8.37  8.52  8.54   .00  -.02 1.04                          .0
S 0 14.91 15.06  .11 1.04
TRQ  164.1  61  72  P 0 1015 25.44 25.59 25.74   .00  -.15 1.04                          .0
 A
VDQ  325.8 339  48  P 0 1015 46.81 46.96 47.00   .00  -.04 1.04                          .0
 A
JAQ  921.8   3  48  P 0 1015119.67119.82119.68   .00   .14 1.04                          .0
 A
WBO  104.2 122  72    4 1015                     .00                                    .0
S 1 28.44 28.59 -.06  .78
```

Recomputed locations for local events using HYPOCENTER code.

——— HYPOCENTER VERSION 1.2 8/19/86 ———

```
RESET TEST( 1)=  10.0000
RESET TEST( 2)= 500.0000
RESET TEST( 3)=    .5000
RESET TEST( 5)=  15.0000
RESET TEST( 6)=   1.0000
RESET TEST(11)=  20.0000
RESET TEST(13)=  10.0000
RESET TEST(30)=    .0050
RESET TEST(31)=   3.0000
RESET TEST(36)=    .0000
RESET TEST(37)=   6.0000
RESET TEST(33)=    .0000
RESET TEST(41)=1000.0000
RESET TEST(42)=    .0000

 SANY4310.43N 7852.22W 172   .00  .00
 CROG4354.30N 7524.75W 244   .00  .00
 DANY4450.14N 7345.43W 507   .00  .00
 DHN 4249.53N 7811.58W 491   .00  .00
 MEO 4401.11N 7822.46W 149   .00  .00
 OTT 4523.65N 7543.00W  77   .00  .00
 MBO 4500.01N 7516.50W  85   .00  .00
 CKO 4559.66N 7727.00W 190   .00  .00
 MEDY4310.91N 7823.42W 186   .00  .00
 PNY 4450.05N 7333.30W 177   .00  .00
 LDO 4100.25N 7354.55W  91   .00  .00
 PAL 4100.25N 7354.55W  91   .00  .00
 PTN 4434.35N 7458.97W 238   .00  .00
 GAC 4542.20N 7528.70W  62   .00  .00
 GRO 4636.40N 7551.60W 290   .00  .00
 TRO 4613.33N 7433.34W 853   .00  .00
 EED 4638.46N 7904.38W 398   .00  .00
 ALX 4419.35N 7555.68W 121   .00  .00
 DNY 4250.18N 7810.13W 381   .00  .00
 CFO 4528.15N 7613.75W  70   .00  .00
 MIO 4622.20N 7558.20W 199   .00  .00
 LN  4408.70N 7651.75W  93   .00  .00
 MNT 4530.15N 7337.40W 112   .00  .00
 BNT 4621.76N 7222.33W  10   .00  .00
 SUD 4627.99N 8058.57W 267   .00  .00
 VDQ 4813.80N 7758.30W 305   .00  .00

Geophysics Division, Geological Survey of Canada (OTTAWA) Crustal Velocity Model

 6.200   .000   .000
 8.200 36.000   .000

  FIRST ARRIVAL =  831011  4 10 59.54
```

```
 ITER   ORIGIN   LAT N   LONG W DEPTH NO  W    RMS   DAMP.   ERLG  ERLT  ERDP
        (SEC)  (DG MN) (DG MN)  (KM)              (SEC)          (KM)  (KM)  (KM)
   1    55.97 4523.73 7542.99 15.00 15  2 2.457   .005    .0    .0    .0
   2    55.13 4513.01 7547.01 15.00 15  2  .505   .005   5.5   5.6   9.6
   3    55.06 4512.29 7546.90 15.00 15  2  .478   .005   1.1   1.1    .6
 DEPTH FREED: ICD=  3
   4    55.01 4512.16 7547.21 13.98 15  3  .468   .005   1.2   1.1   1.3
 DEPTH FIXED: ICD=  3
   5    55.00 4512.15 7547.23 13.96 15  2  .468   .005   1.2   1.1   1.3

  DATE      ORIGIN   LAT N   LONG W DEPTH NO  W    RMS DAMP. ERLN ERLT ERDP ICD
831011  4 10 55.00 4512.15 7547.23 14.0  15  3  .468 .005  1.2  1.1  1.3   3

DRMS VALUES: D=  10.00 KM

DRMS:       LON+D    LON-D    LAT+D    LAT-D   DEPTH+D  DEPTH-D
 DRMS POS     .80      .86      .80      .79      .79      .29

RESOLUTION MATRIX:          LONG     LAT   DEPTH
                   LONG     .993   -.002   -.003
                   LAT     -.002    .994   -.002
                  DEPTH    -.003   -.002    .993

  STN  DIST AZM AIN PWAV HRMN P-SEC TPOBS TPCAL DLY/HI P-RES P-WT AMX PRX CALI K XMAG RWK FMP FMAG S
RWK S-SEC TSOBS S-RES  S-WT
 ALX   98.1 186  81  P 1  410 71.31 16.31 15.98   .00   .32   .80                              .0
  4
 OTT   21.9  13  81  PDO  410 59.54  4.54  4.19   .00   .35  1.07                              .0
S 0 62.42  7.42   .09  1.07
 MBO   47.1 118  81  PDO  410 62.87  7.87  7.92   .00  -.05  1.07                             4.4
S 0 68.19 13.19  -.67  1.07
 GAC   60.3  22  81  PDO  410 65.22 10.22  9.99   .00   .23  1.07                             4.3
S 0 72.20 17.20  -.28  1.07
 CKD  159.8 304  49  PCO  410 80.37 25.37 25.62   .00  -.25  1.07                             4.6
S 0 99.12 44.12  -.71  1.07
 MNT  174.9  79  49  PDO  410 81.73 26.73 27.45   .00  -.72  1.07                             4.7
S 1104.02 49.02   .98   .80
 SNT  296.8  64  49  PCO  410 97.73 42.73 42.32   .00   .40  1.07                              .0
  4
 VDG  379.3 333  49  P 1  410107.30 52.30 52.39   .00  -.09   .80                              .0
  4
 SUD  435.6 289  49  P 1  410114.30 59.30 59.25   .00   .25   .80                             5.6
  4
 MED  244.4 238  49  PCO  410 91.45 36.45 35.94   .00   .51  1.07                             5.1
  4

UNWEIGHTED RMS =   .47
```

AVERAGE STATION RESIDUALS (WEIGHTED):

STATION	P RESIDUAL	NO P	S RESIDUAL	NO S
MED	.55	1		
OTT	.38	1	.10	1
WBO	-.06	1	-.72	1
CKO	-.27	1	-.76	1
GAC	.25	1	-.30	1
ALX	.26	1		
MNT	-.77	1	.79	1
GNT	.43	1		
SUD	.20	1		
VDO	-.07	1		

Lamont-Doherty Geological Observatory (LDGO) Crustal Velocity Model

6.100 .000 .000
6.650 4.000 .000
8.100 35.000 .000

FIRST ARRIVAL = 831011 4 10 59.54

ITER	ORIGIN (SEC)	LAT N (DG MN)	LONG W (DG MN)	DEPTH (KM)	NO	M	RMS (SEC)	DAMP.	ERLG (KM)	ERLT (KM)	ERDP (KM)
1	56.80	4523.73	7542.89	15.00	15	2	2.388	.005	.0	.0	.0
2	55.94	4512.54	7546.14	15.00	15	2	.600	.005	4.9	5.7	17.8
3	55.93	4512.39	7545.93	15.00	15	2	.598	.005	1.3	1.4	1.5
DEPTH FREED: ICD= 3											
4	55.86	4511.76	7546.29	9.91	15	3	.506	.005	1.3	1.5	2.0
5	55.86	4511.88	7546.50	10.68	15	3	.502	.005	1.1	1.2	2.8
6	55.86	4511.87	7546.51	10.59	15	3	.502	.005	1.1	1.2	2.6
DEPTH FIXED: ICD= 3											
7	55.86	4511.87	7546.51	10.60	15	2	.502	.005	1.1	1.2	2.6

DATE	ORIGIN	LAT N	LONG W	DEPTH	NO	M	RMS	DAMP.	ERLN	ERLT	ERDP	ICD
831011	4 10 55.86	4511.87	7546.51	10.6	15	3	.502	.005	1.1	1.2	2.6	3

DRMS VALUES: D= 10.00 KM

DRMS:	LON+D	LON-D	LAT+D	LAT-D	DEPTH+D	DEPTH-D
DRMS POS	.90	.93	.78	.75	.53	.12

RESOLUTION MATRIX:

	LONG	LAT	DEPTH
LONG	.994	-.002	-.003
LAT	-.002	.994	-.003
DEPTH	-.003	-.003	.993

STN	DIST	AZM	AIN	PRMK	HRMN	P-SEC	TPOBS	TPCAL	DLY/HI	P-RES	P-WT	AMX	PRX	CALX	K	XMAG	RMK	FMP	FMAG	S
RMK	S-SEC	TSOBS	S-RES	S-WT																
ALX	97.7	187	66	P	1	410	71.31	15.45	14.99	.00	.46	.80							.0	

ITER	ORIGIN (SEC)	LAT N (DG MN)	LONG W (DG MN)	DEPTH (KM)	NO	M	RMS (SEC)	DAMP.	ERLG (KM)	ERLT (KM)	ERDP (KM)
1	56.35	4523.73	7542.89	15.00	15	2	2.418	.005	.0	.0	.0
2	55.48	4512.83	7546.93	15.00	15	2	.508	.005	5.1	5.6	11.9
3	55.42	4512.27	7546.82	15.00	15	2	.492	.005	1.0	1.2	.9
DEPTH FREED: ICD= 3											
4	55.33	4511.93	7547.33	12.15	15	3	.434	.005	1.1	1.2	1.6
5	55.32	4511.91	7547.34	11.95	15	3	.433	.005	.9	1.0	1.5
DEPTH FIXED: ICD= 3											
6	55.32	4511.91	7547.34	11.95	15	2	.433	.005	.9	1.0	1.5

DATE	ORIGIN	LAT N	LONG W	DEPTH	NO	M	RMS	DAMP.	ERLN	ERLT	ERDP	ICD
831011	4 10 55.32	4511.91	7547.34	11.9	15	3	.433	.005	.9	1.0	1.5	3

DRMS VALUES: D= 10.00 KM

	LON+D	LON-D	LAT+D	LAT-D	DEPTH+D	DEPTH-D
DRMS POS	.90	.95	.83	.81	.58	.29

RESOLUTION MATRIX:

	LONG	LAT	DEPTH
LONG	.994	-.002	-.002
LAT	-.002	.994	-.002
DEPTH	-.002	-.002	.994

STN	DIST	AZM	AIM	PRMK	HRMN	P-SEC	TPOBS	TPCAL	DLY/HI	P-RES	P-WT	AMX	PRX	CALX	K	XMAG	RMK	FMP	FMAG	S
RMK	S-SEC	TSOBS	S-RES	S-WT																
ALX	97.6	186	71	P	1	410	71.31	15.99	15.41	.00	.59	.80								.0
4																				
OTT	22.4	13	57	PD0		410	59.54	4.22	3.98	.00	.25	1.07								.0
S 0	62.42	7.10	.14	1.07																
WBO	47.0	117	67	PD0		410	62.87	7.55	7.60	.00	-.05	1.07								4.4
S 0	68.19	12.87	-.43	1.07																
SAC	60.8	22	69	PD0		410	65.22	9.90	9.71	.00	.19	1.07								4.3
S 0	72.20	16.88	-.11	1.07																
CKD	159.9	304	67	PC0		410	80.37	25.05	25.06	.00	-.01	1.07								4.6
S 0	99.12	43.90	-.06	1.07																
MNT	175.1	78	49	PD0		410	81.73	26.41	27.14	.00	-.72	1.07								4.7
S 1	104.02	48.70	1.21	.80																
BNT	297.1	64	49	PC0		410	97.73	42.41	42.39	.00	.02	1.07								.0
4																				
VDG	379.7	333	49	P	1	410	107.30	51.98	52.71	.00	-.73	.80								.0
4																				
SUD	435.6	289	49	P	1	410	114.50	59.18	59.70	.00	-.52	.80								5.6
4																				
MED	244.1	238	49	PC0		410	91.45	36.13	35.76	.00	.37	1.07								5.1
4																				

UNWEIGHTED RMS = .49

AVERAGE STATION RESIDUALS (WEIGHTED):

```
 4
 OTT   22.2  11  57  PD0  410 59.54  3.68  3.81   .00  -.13  1.07                .0
S 0 62.42  6.56  -.11  1.07
 WBO   46.0 118  64  PD0  410 62.87  7.01  7.26   .00  -.25  1.07               4.4
S 0 68.19 12.33  -.38  1.07
 GAC   60.4  21  65  PD0  410 65.22  9.36  9.41   .00  -.05  1.07               4.3
S 0 72.20 16.34  -.13  1.07
 CKO  160.9 304  66  PC0  410 80.37 24.51 24.48   .00   .03  1.07               4.6
S 0 99.12 43.26   .42  1.07
 MNT  174.0  78  66  PD0  410 81.73 25.87 26.45   .00  -.58  1.07               4.7
S 1104.02 48.16  1.88   .80
 GNT  296.2  64  48  PC0  410 97.73 41.87 41.75   .00   .12  1.07                .0
 4
 VDQ  380.2 333  48  P 1  410107.30 51.44 52.13   .00  -.69   .80                .0
 4
 SUD  436.7 289  48  P 1  410114.50 58.64 59.10   .00  -.46   .80               5.6
 4
 MED  245.0 238  48  PC0  410 91.45 35.59 35.43   .00   .16  1.07               5.1
 4

UNWEIGHTED RMS =   .59


AVERAGE STATION RESIDUALS (WEIGHTED):

STATION     P RESIDUAL  NO P     S RESIDUAL  NO S
MED              .17     1
OTT             -.14     1          -.12     1
WBO             -.27     1          -.40     1
CKO              .03     1           .45     1
GAC             -.06     1          -.14     1
ALX              .37     1
MNT             -.62     1          1.31     1
GNT              .13     1
SUD             -.37     1
VDQ             -.55     1
```

Crustal Velocity Model Developed In This Study

```
 6.100   .000   .000
 6.400  1.000   .000
 6.600 16.500   .000
 6.800 26.000   .000
 7.000 33.000   .000
 8.100 37.000   .000

  FIRST ARRIVAL =  831011  4 10 59.54
```

STATION	P RESIDUAL	NO P	S RESIDUAL	NO S
MED	.40	1		
OTT	.26	1	.15	1
MBO	-.05	1	-.46	1
CKO	-.01	1	-.06	1
GAC	.21	1	-.12	1
ALX	.47	1		
MNT	-.78	1	.98	1
GNT	.02	1		
SUD	-.42	1		
VDQ	-.58	1		